CRITICAL REVIEW OF PHOTOVOLTAIC RESEARCH AND DEVELOPMENT

Prepared For:

Renewable Energy Branch
Energy, Mines and Resources Canada
Ottawa, Ontario, Canada
DSS Contract File No. 23216-6-6107
1987 August 10

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Citation

Vikis, A.C., F. Garisto, Atomic Energy of Canada Ltd. Critical Review of Photovoltaic Research and Development Report of Contract File no.23216-6-6107. Renewable Energy Branch; Energy, Mines and Resources Canada. Ottawa, Ontario. 1987 (79 pages)

Copies of this report may be obtained through:

Renewable Energy Branch
Energy, Mines and Resources Canada
580 Booth Street
Ottawa, Ontario
K1A 0E4

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Catalogue no.: M91-7/17-1988E

ISBN no.: 0-662-16300-1

Funding for this report was provided by the Panel of Energy Research and Development, Office of Energy Research and Development, Energy Mines and Resources Canada

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ABSTRACT

This study examines technological and other related developments in photovoltaics, and assesses the prospects of future applications of this technology to generate electricity at costs competitive with conventional means. Photovoltaics is also examined from a Canadian perspective and recommendations are provided for on appropriate R&D strategy to maximize the benefits from this technology in Canada. The study concludes that significant scientific and engineering advances are still required before photovoltaics can be considered an economically viable method of generating electricity; however, recent advances in thin-film solar cells make this goal seem more realistic and near-term. The study recommends that Canada should embark on a mission-oriented national program in photovoltaics in order to maximize benefits from present and future applications of this technology at home and abroad.

EXECUTIVE SUMMARY

This study examines worldwide developments in photovoltaics, particularly technology advances and limitations, and assesses the prospects for the future application of photovoltaics to generate electricity at costs competitive with conventional means. Photovoltaics is also examined from a Canadian perspective and recommendations are made for an appropriate R&D strategy to maximize benefits from this technology in Canada.

Extensive R&D in photovoltaics during the last decade, prompted by the energy crisis of the seventies, has led to significant advances in the terrestrial application of photovoltaics. Photovoltaic power systems are presently displacing expensive electricity sources (batteries, thermoelectric and thermomechanical generators, etc.) in a variety of consumer and industrial applications; also several demonstrations of utility-grid applications ranging in size from 10 kWp to 7 MWp, have been built. Over the last decade, such applications have led to an exponential growth in the demand for photovoltaic power cells. In 1986, about 30 MWp of photovoltaic power cells were produced which amounted to an overall market of about a billion dollars (U.S.) per annum. At their current growth rate, such markets are forecast to reach about 80 MWp per annum by 1995 and about 130 MWp per annum by the year 2000.

Photovoltaic cell demand of the order of gigawatts per annum would be required when megawatt-size power plants, generating electricity at costs competitive with conventional means, become technically and economically feasible. To achieve this goal, significant scientific and engineering advances are still required to increase the efficiency of photovoltaic cells to about 15%, to increase their lifetime to about 30 years, and to reduce their manufacturing costs to less than about a dollar (U.S.) per peak watt. Recent advances in thin-film solar cell technology, such as the development of new materials (amorphous-silicon, copper indium diselenide and cadmium telluride), make this goal seem realistic.

It is generally accepted by the experts that the most critical challenge, before photovoltaics can be deployed economically for bulk electricity generation, is reducing the cost of photovoltaic modules. This could be accomplished by reducing material costs and/or by increasing the rate of module fabrication through automation. Conventional technologies based on single crystal and polycrystalline silicon are material intensive and not amenable to high fabrication rates. Ribbon silicon technologies are better in terms of materials demand, but still suffer in terms of fabrication rates. Also, the much higher cost of gallium arsenide solar cells precludes their use in terrestrial applications, except in concentrator-type solar power systems that are of limited applicability. There is also a general view in the scientific community that these technologies have reached a stage of

maturation and thus are unlikely to yield the required order of magnitude improvements. It is thus no surprise that the bulk of the R&D effort, worldwide, is now focussing on thin-film materials and in particular amorphous silicon.

The most prominent thin-film materials under study are amorphous silicon, cadmium telluride, and copper indium diselenide. These materials have several advantages over the conventional crystalline and semicrystalline silicon wafer materials. Material requirements are reduced by about a factor of one hundred, due to the much higher optical absorption coefficients of the thin film materials. No sawing is required, hence material loss is avoided and film deposition, including doping and junction formation, can be done in a continuous and fully-automated process. The resulting high fabrication rates translate into reduced costs. This study concludes that the thin-film materials of most promise are those based on amorphous silicon (a-Si) and its alloys (a-SiGe:H and a-SiC:H). Given the present level of R&D effort in thin-film solar cells, it is projected that module efficiencies, lifetimes and costs, required for generating electricity at costs competitive with conventional means for the U.S. Southwest and equivalent climactic and economic conditions, will be achieved by about the year 2000. Needless to say, market forces relating to supply and demand of conventional fuels, as well as political considerations, would play a major role in whether and how soon photovoltaic power systems would be implemented in utility electricity generation.

In Canada, because of a more secure energy future, as well as less favourable climatic conditions, photovoltaic power systems have not received the major thrust seen in other countries, i.e. the U.S.A., Japan and Europe. Photovoltaic R&D is presently funded at a level of about $2 M (Can.) by Energy Mines and Resources Canada, the Natural Sciences and Engineering Research Council and, to a lesser extent, by various other federal and provincial departments. Such R&D is presently conducted in industry, universities and various other research institutions and includes, for example, materials and device research, module and cell processing technology, and system development and performance evaluation.

Canada is already benefiting from the application of photovoltaic power systems in communications, monitoring and sensing equipment, marking and warning devices, as well as in a variety of consumer products (watches, calculators, etc.). New applications, expected to become economic with future technology advances, are in corrosion protection, water pumping, remote lighting, photovoltaic/diesel hybrids, and ultimately utility-grid applications. However, in Canada, because of abundant conventional energy resources and less favourable climatic conditions, the technological

barriers that must be overcome are more challenging and, hence the prospects of generating electricity by photovoltaics, at costs competitive with our current means, are more long-term. Thus, photovoltaics are not likely to be a substantial component (> 5%) of the Canadian electricity mix early into the 21st century, unless technology advances exceed current expectations, and political and economic factors dictate the use of alternative energy resources.

The present study recommends that to maximize benefits from current photovoltaic applications and be in a position to benefit from near-term foreign markets in photovoltaic power systems, as well as from longer-term power applications at home, Canada must embark now on a mission-oriented national program in photovoltaics.

RÉSUMÉ

La présente étude porte sur les perfectionnements technologiques et sur d'autres perfectionnements connexes en matière d'énergie photovoltaique, et évalue les possibilités d'applications futures de cette forme d'énergie pour la production d'électricité à des coûts concurrentiels avec ceux des moyens classiques. On envisage aussi l'énergie photovoltaique en tenant compte du contexte canadien et on fait des recommandations relatives à une stratégie appropriée de R et D en vue de maximiser les avantages de cette forme d'énergie au Canada. L'étude permet de conclure que des progrès scientifiques et techniques sont encore nécessaires avant que l'énergie photovoltaique puisse être considérée comme un moyen rentable de production d'électricité; cependant, en raison des progrès récents dans le domaine des photopiles en couches minces, cet objectif semble plus réaliste et réalisable à court terme. L'étude contient des recommandations selon lesquelles le Canada devrait s'engager dans un programme national orienté vers un vut précis en matière d'énergie photovoltaique afin de maximiser les avantages des applications actuelles et futures au Canada et à l'étranger.

La présente étude porte sur les perfectionnements réalisés dans le monde entier en matière d'énergie photovoltaique, particulièrement sur les progrès et les limites technologiques, et elle évalue les possibilités d'applications futures pour la production d'électricité à des coûts concurrentiels avec ceux des moyens classiques. On envisage aussi l'énergie photovoltaique en tenant compte du contexte canadien et on fait des recommandations relatives à une stratégie appropriée de R et D en vue de maximiser ses avantages au Canada.

Les travaux approfondis de R et D en matière d'énergie photovoltaique au cours de la dernière décennie, suscités par la crise énergétique des années 70, ont permis des progrès importants pour les applications terrestres. Les systèmes photovoltaiques remplacent présentement les sources d'électricité coûteuses (accumulateurs, générateurs thermoélectriques et thermo-mécaniques, etc.) dans une variété d'applications orientées vers le grand public ou vers l'industrie; de plus, plusieurs démonstrations d'applications branchées aux réseaux électriques, à des puissances de 10kWc à 7 MWc, ont été réalisées. Au cours de la dernière décennie, ces applications ont entraîné une croissance exponentielle de la demande de cellules photovoltaiques. En 1986, on a produit des cellules photovoltaiques d'une puissance totale de 30 MWc représentant un marché global d'environ un milliard de dollars (américains) par année. À son taux de croissance actuel, ce secteur de marché devrait représenter environ 80 MWc par année en 1995 et environ 130 MWc par année en l'an 2000.

Il faudrait que la demande d'énergie fournie par des cellules photovoltaiques soit de l'ordre des gigawatts par année pour que des centrales ayant des puissances de l'ordre du mégawatt et produisant de l'électricité à des coûts concurrentiels avec ceux des moyens classiques deviennent réalisables techniquement et rentables. Pour atteindre cet objectif, il faudra encore réaliser des progrès scientifiques et techniques importants afin d'accroître le rendement des cellules photovoltaiques jusqu'à environ 15 %, de porter leur durée de vie à environ 30 ans et de réduire leur coût de fabrication à moins d'un dollar (américain) par watt crête. En raison des perfectionnements récents dans la technologie des photopiles en couches minces, par exemple la mise au point de nouveaux matériaux (silicium amorphe, diséléniure de cuivre et d'indium et tellurure de cadmium), cet objectif semble réaliste.

Les spécialistes reconnaissent généralement que l'étape la plus critique à franchir avant que l'énergie photovoltaique puisse être utilisée de façon rentable pour la production d'électricité en grande quantité est la réduction du coût des modules photovoltaiques. On pourrait y arriver par la réduction du coût des matériaux ou l'accroissement du taux de fabrication de modules au moyen de l'automatisation, ou les deux. Les techniques classiques basées sur le silicium monocristallin et le silicium polycristallin consomment beaucoup de matériaux et ne permettent pas des taux de fabrication élevés. Les technques basées sur le silicium en ruban consomment moins de matériaux, mais elles ne permettent pas encore des taux de fabrication suffisants. De plus, étant donné leurs coûts beaucoup plus élevés, les photopiles à

arséniure de gallium ne peuvent pas être utilisés dans des applications terrestres, sauf dans les systèmes à énergie solaire à concentrateurs, dont les possibilités d'applications sont limitées. De plus, on reconnaît généralement dans la communauté scientifique que ces techniques ont atteint un stade de maturité et qu'il est peu probable qu'elles puissent être améliorées dans la mesure recherchée. Il n'est donc pas étonnant que la plus grande partie des travaux de R et D, dans le monde entier, soient maintenant axés sur les matériaux en couches minces, particulièrement le silicium amorphe.

Les principaux matériaux en couches minces qui sont à l'étude sont le silicium amorphe, le tellurure de cadmium et le diséléniure de cuivre et d'indium. Ces matériaux offrent plusieurs avantages par rapport aux tranches de silicium cristallin et semi-cristallin classiques. Les besoins en matériaux sont réduits par un facteur d'environ 100 en raison des coefficients d'absorption optique beaucoup plus élevés des matériaux en couches minces. Aucun découpage n'est requis, ce qui élimine les pertes de matériaux, et le dépôt de couches, y compris le dopage et la formation de jonctions, peut être réalisé dans un processus continu entièrement automatisé. Les taux élevés de fabrication qui en résultent se traduisent par une réduction des coûts. La présente étude permet de conclure que les matériaux en couches minces les plus prometteurs sont les matériaux à base de silicium amorphe (a-Si) et de ses alliages (a-SiGe:H et a-SiC:H). D'après le niveau actuel des efforts consacrés à la R et D en matière de photopiles en couches minces, on prévoit que les critères d'efficacité, de durée et de coût auxquels il

faut répondre pour produire de l'électricité à des coûts concurrentiels avec ceux des moyens classiques dans le sud-ouest des É.-U. et les régions aux conditions climatiques et économiques équivalentes seront satisfaits vers l'an 2000. Est-il nécessaire de mentionner que les forces du marché en matière d'offre et de demande de combustibles classiques de même que les considérations politiques joueraient un rôle déterminant dans la décision d'appliquer ou non les systèmes photovoltaiques à la production d'électricité destinée au réseau public et sur la rapidité à laquelle on procéderait à cette application.

Au Canada, les systèmes photovoltaiques n'ont pas connu une aussi grande popularité par rapport à l'étranger, tels les États-Unis, le Japon et l'Europe étant donné une plus grande sécurité face à l'avenir sur le plan de l'énergie et les conditions climatiques moins favorables. La R et D en matière d'énergie photovoltaique est présentement financé à raison d'environ 2 millions de dollars (canadiens) par Énergie. Mines et Ressources Canada, le Conseil de recherches en sciences naturelles et en génie et, à un degré moindre, par différents autres ministères fédéraux et provinciaux. Les travaux de R et D qui sont réalisés présentement dans l'industrie, les universités et différentes autres institutions de recherche portent notamment sur les matériaux et les dispositifs, la technologie de fabrication de modules et de cellules, et la mise au point et l'évaluation du rendement des systèmes.

Le Canada bénéficie déjà de l'application de systèmes photovoltaiques dans les domaines des communications, du matériel de surveillance et de détection, dispositifs de marquage et d'alarme, de

même que dans une variété de produits destinés grand public (montres, calculatrices, etc.). De nouvelles applications, qui devraient devenir rentables avec les perfectionnements technologiques futurs, ont trait à la protection contre la corrosion, au pompage de l'eau, à l'éclairage à distance, aux systèmes hybrides photovoltaiques/diesels, et, finalement, à la production d'électricité destinée au réseau public. Cependant, au Canada, étant donné l'abondance des ressources énergétiques classiques et les conditions climatiques moins favorables, les barrières technologiques sont plus difficiles à franchir et, par conséquent, les possibilités de production d'électricité par des systèmes photovoltaiques à des coûts concurrentiels avec ceux de la production par nos moyens actuels doivent être envisagés à plus long terme. Il est donc peu probable que les systèmes photovoltaiques représentent une part importante (5 %) du marché canadien de l'électricité au début du XXI^{e} siècle, à moins que les progrès technologiques dépassent les prévisions actuelles et que des facteurs politiques et économiques dictent l'utilisation de ressources énergétiques de rechange.

La présente contient des recommandations selon lesquelles pour maximiser les avantages tirés des applications actuelles de l'énergie photovoltaique et pour être en mesure de bénéficier des marchés étrangers des systèmes photovoltaiques à court terme de même que des applications à plus long terme au pays, le Canada doit s'engager dès maintenant dans un programme national orienté vers un but précis en matière d'énergie photovoltaique.

1. INTRODUCTION

In many of the industrialized countries, the energy crisis of the seventies led to a wide range of energy conservation measures and spurred the search for alternative energy resources. Amongst these, photovoltaic power systems, which convert solar radiation directly to electrical power, have received considerable attention during the last decade. The novelty of photovoltaic R&D, ongoing activities in space applications, parallel research in the semiconductor field, as well as a large influx of government funding, have generated the proper climate for significant breakthroughs in this field. The rate of progress achieved in the past decade, as well as the continued escalation of conventional energy costs, have led to the belief that photovoltaic power systems should, in the next decade or so, become a technically and economically viable option for generating electricity.

There is no doubt that photovoltaic technology today is making substantial inroads in a variety of specialized applications. Photovoltaic power systems are presently displacing expensive electricity sources in a variety of consumer and industrial applications, and several demonstrations of utility-grid applications, ranging in size from 10 kW to 7 MW, have been built. Photovoltaic power plants, larger than 100 MW and generating electricity at costs competitive with conventional means, are forecast to be in place by the year 2000. To achieve this goal, significant scientific and engineering advances are required to increase the efficiency and lifetime of photovoltaic modules and reduce manufacturing costs. Recent advances in thin-film solar cell technology, such as the development of new materials (amorphous-silicon, copper indium diselenide and cadmium telluride), make this goal seem more realistic. Needless to say, market forces relating to supply and demand of conventional energy resources would play a major role in whether and how soon photovoltaic power systems would be implemented in utility electricity generation.

In Canada, because of a more secure energy future, as well as non-ideal climatic conditions, photovoltaic power systems have not received the major thrust seen in other countries, i.e., the U.S.A. and Japan. Canadian photovoltaic R&D was until October 1984, mainly sponsored by the Energy Project of the National Research Council of Canada. Photovoltaic R&D is presently funded at a level of about $2 M (Can.)* by Energy, Mines and Resources Canada (EMR), the Natural Sciences and Engineering Research Council and, to a lesser extent, by various other federal and provincial departments. Such R&D is presently conducted in industry, universities and various other research institutions and includes, for example, materials and device research, module and cell production technology, and system development and performance evaluation.

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* All dollar amounts are expressed in U.S. dollars ($U.S. = $1.35 Can.) unless otherwise indicated.

To address Canada's role in this rapidly evolving field, the Solar Energy Development Program of the Renewable Energy Branch of EMR, commissioned this study, with the following rationale and objectives. Aside from maintaining some photovoltaic R&D in order to remain abreast of developments in this field, a large Canadian involvement may not be required at present and, in view of R&D budgetary limitations, may be difficult to justify unless a clear need or Canadian niche is identified. Thus, to maximize the return on present or future R&D investment, it is important to examine worldwide developments in this field and to identify potential opportunities and spin-offs that might benefit Canada, either through application of this technology at home or through the sale of Canadian technology abroad.

Atomic Energy of Canada Limited (Research Company), through partial (25%) funding of this study, was interested in identifying areas of photovoltaic R&D where indigenous resources and expertise - acquired through a multidisciplinary approach to the solution of nuclear energy problems - can be deployed for the benefit of the Company and the Canadian public in general.

To address the above objectives, we first examined the scientific literature to identify technology advances and limitations, and to assess the prospects of resolving such limitations in the future. Recognizing that R&D activities cannot be viewed in isolation from products, markets and market economics, we also examined these and had them feature directly into our evaluations. Finally, to assess the relevance of this technology to Canada, we examined Canadian resources and expertise and the prospects of exploitation of this technology in Canada. Based on our findings in this study, we formulated recommendations for an appropriate photovoltaic R&D strategy in Canada.

2. EVOLUTION OF PHOTOVOLTAICS

The photovoltaic (PV) effect, the direct conversion of light into electricity, was first observed in a solid (selenium) by Adams and Day [1] in 1877. However, the modern age of solar cell development did not begin until 1954 when Bell Labs [2] made the first silicon p-n junction solar cell. The efficiency of these early cells was less than 5% but by 1958 efficiencies of up to 14% were obtained as a result of improvements in fabrication processes and in the theoretical understanding of device operation. Although application of these cells to generate electricity in remote sites could be envisaged, this technology remained more of a curiosity than a practical energy source because of the high costs of the solar cells.

The PV industry received a major boost in the late fifties as a result of the emerging space age, once it became apparent that solar cells were a viable power source for space satellites. Solar cells could provide power for long times (compared with chemical batteries) at minimum weight and cost. Space applications require reliable and radiation resistant solar cells. Improvements in these aspects of PV technology were the driving engineering goals in PV

development in the sixties. In addition, the PV industry benefited significantly, as it does today, through advances in the much larger semiconductor industry. In spite of the advances in PV technology, solar cells were not a power option for terrestrial applications in the sixties.

The next major boost to PV development arose as a result of the energy crisis in the early seventies. Concerns about energy security, especially in the United States, resulted in expanded R&D programs in renewable and alternative energy sources. PV, with its evident advantages: free "fuel", reliable and pollution free operation, and optimistic cost projections, received its share of the R&D budget in renewable energy. In fact, between 1975 and 1986 spending on PV R&D in the United States alone amounted to 1.5 billion dollars [3]. The ultimate aim of the United States program was and is to provide PV utility power at costs competitive with conventional power generation.

The original U.S. Department of Energy (DOE) goals for PV power costs were too optimistic. For flat plate arrays the cost goals in 1977 were: $2 per peak watt (Wp) by 1982 and $0.50/Wp by 1986 [4]. (The power output of solar cells is rated in peak watts, that is, the wattage the cells would deliver when exposed to sunlight at an intensity of 1000 W/m^2.) These original goals have not been met and are ~ 10 years behind schedule, considering that PV flat-plate modules can today be purchased in large lots for ~ $5/Wp. Nevertheless, dramatic cost reductions have been made. Between 1975 and 1985, the cost of flat-plate PV modules have decreased by a factor of ten. This has led to terrestrial applications of PV power systems at remote sites for communications, monitoring and navigational aids. Further significant cost reductions will require the introduction of either new production methods for crystalline-silicon solar cells or newer technologies, e.g., thin-film solar cells.

An important PV development in the seventies was the emergence of thin film technologies, in particular, amorphous silicon thin films. Hydrogenated amorphous silicon (a-Si:H) solar cells were first fabricated by Carlson and Wronski [5] in 1976. Since then the Japanese have successfully adapted this technology for battery replacement in consumer products such as watches and calculators. This is a rapidly growing market for solar cells and today about 35% of all solar cells are used for consumer applications. Because of automated production and the reduced requirements for highly purified silicon, thin film technologies hold the promise of PV utility power [6-11] in the late 1990's. However, some fundamental problems [8-11] must still be solved if this goal is to be attained.

The energy crisis of the seventies disappeared in the eighties as a result of the world recession, increased oil exploration and government programs for energy conservation. Thus, interest in renewable and/or alternative energy sources waned and the R&D budgets for these programs were

slashed. Cutbacks in PV R&D funding have been quite severe, e.g., from $150 million in 1980 to $43 million in 1986 at the DOE [12]. (The current level of PV funding is probably safe [13].) These cutbacks, as well as the difficulty in improving a maturing crystalline-silicon solar cell technology, are partially responsible for the 10 year lag in the schedule for PV module cost reductions and the recent static costs for PV modules [14].

The driving force for PV development, in the long term, will come from the utility electricity market and, in the short term, from the consumer products market. The demand for amorphous silicon solar cells for consumer products is expected to grow in the foreseeable future [11]. However, within the next decade, the current non-consumer markets for PV cells, e.g., communications, remote sensing, and marine aids, will saturate and PV demand could drop unless new applications for PV cells are exploited. These new markets are essential to support the PV industry until PV utility power becomes a reality. New markets could, for example, be found in replacement of diesel generators at remote sites, village power both in Canada's north and in third world countries, PV water pumping and PV corrosion protection.

Village-power markets will require development of PV/hybrid systems to provide uninterrupted power when the sun does not shine. This is especially true in Canada's north where insolation levels are low and vary considerably from summer to winter. Because of the high cost of battery storage, we do not expect stand-alone PV/battery systems to be a viable option for village power.

Today, PV systems are mainly used in remote sites where the reliability of the PV power source reduces operating and maintenance costs. However, the high reliability of PV power systems will not be a major factor in non-remote applications, e.g. village power. Capital costs will be the determining factor for PV/hybrid village power systems unless fuel prices increase significantly.

In the long term, PV power systems must be able to compete head-on with conventional energy sources before they can make a significant contribution to the world's energy supply. PV power must also compete with other renewable energy technologies. Currently, wind power and solar thermal power seem to have an edge over PV power because of their lover capital costs. A recently installed 5 MW wind farm [15], for example, was built at a total cost of $8 million dollars, i.e., $1.6/Wp, and solar thermal stations are being built for about $3.5/Wp. PV power systems on the other hand cost more than $8/Wp.

One need only look at the developments in California, where much of the renewable energy is being supplied by wind farms and solar thermal power stations. More than 1400 MW of wind turbine capacity has been installed in the U.S.A. (mostly in California). In addition, ~ 100 MW of solar thermal generating capacity has been installed and connected to the grid of Southern

California Edison [16]. Furthermore, three 30 MW solar thermal power stations are now being built in the Mojave Desert and there are plans for 12 more plants of similar size [16]. In comparison, the total installed capacity of PV utility power systems is small and no new major installations are now being built. The 7 MW Carrisa Plains PV power plant [3,17], built by ARCO Solar, is the largest PV installation in the world.

In the late nineties, the utility market for high-efficiency solar cells will be substantial, if the price of solar cells decreases and/or energy prices increase. PV power stations do have several important advantages over conventional power plants: (i) they can be built in modular units, thus reducing lead times and interest charges, (ii) they are non-polluting, which is important if more stringent controls are imposed on coal stations, and (iii) they do not require cooling water. However, PV stations only generate power when the sun is shining, thus they can only be used to satisfy peak-power demands and are not suitable as base-load power stations [18]. This is not a major problem in the U.S.A. where peak power demands occur in the summer months. In Canada, however, peak power consumption occurs in the winter months when insolation levels are low. Thus the value of PV power to Canadian utilities is much less than to utilities situated in the Southwest United States.

It is expected that the first large scale (100 MW or more) PV utility plant will be built in the Southwest United States, where insolation levels are high, electricity costs are high and capital funds are available. The latter consideration is important. Many third world countries also have high insolation levels and expensive electricity (if it is available at all) but do not have the funds to install PV utility systems. Thus, Canada could help its emerging PV industry by using some of its foreign aid funds to install PV systems in third world countries.

3. PHYSICS OF PHOTOVOLTAICS

3.1 THE SOLAR ENERGY SOURCE

The solar constant is defined as the rate at which solar energy is received by a unit surface, perpendicular to the sun's direction, in free space at the mean distance from the sun. The solar constant is equal to 1353 W/m^2 [19].

The spectrum of solar radiation reaching the earth's surface is changed considerably [19,20] from that in free space by selective absorption of certain wavelength photons by atmospheric gases, e.g., O_2, O_3, H_2O and CO_2. The optical air mass, m, is used to describe the effect of the atmosphere on the intensity and spectrum of the solar energy reaching the earth. It is defined as the path length of radiation through the atmosphere considering the vertical path at sea level as unity. Air mass zero (m = 0, written AM0) corresponds to

the solar spectrum in free space. The air mass 1.5 solar spectrum (AM1.5) is now the standard spectrum for measuring the efficiency of solar cells [21]. On a clear day, the total solar energy falling on a flat surface is 1.06, 0.88 and 0.75 kW/m^2 for air masses of 1, 2 and 3, respectively [19].

Reliable insolation data are required to design optimal solar energy systems. (Site specific insolation data would, of course, permit the best design.) Environment Canada, through the Atmospheric Environment Service, is compiling historical solar radiation data files [22,23], and is conducting solar spectrum and site specific solar studies. A recent publication [24] provides hourly solar radiation data for 144 Canadian locations.

Solar radiation is quite diffuse. For Canada, for example, the average daily solar radiation falling on a 1 m^2 surface yields the energy equivalent of only 1/3 litres of oil (about 14 MJ) [23]. Therefore, large capture areas are needed for large-scale solar energy installations. In addition, the intensity of solar radiation fluctuates between summer and winter, day and night, and from day to day. Thus, unlike the usual power sources, solar power systems cannot provide power on-demand.

The annual solar radiation received in the southern part of Canada is comparable to that received by most countries [20]. However, the seasonal distribution of solar energy is important in determining the economic viability of PV systems. Canada receives the majority of its solar energy during the long, sunny, summer days and considerably less during the short winter days. Thus, for Canada, the peak in solar energy supply is opposite to that of electricity demand [25,26].

3.2 BASIC PHYSICS OF PHOTOVOLTAICS

Photovoltaic cells (see Figure 1) are based on semiconductor technology, i.e. the p-n junction. Either homojunction cells or heterojunction cells are manufactured. In homojunction cells the p- and n-doped materials are made from the same semiconductor, e.g. the p-Si/n-Si solar cell. In heterojunction cells the p- and n-doped materials are made from different semiconductors, e.g. the $CdS/CuInSe_2$ solar cell, in which CdS is n-type and $CuInSe_2$ is p-type. All solar cells convert light into electricity in the same way. The physics of PV electricity generation is briefly described in the following paragraphs. **Readers who are already familiar with the physics of solar cells or are not interested in these details may proceed directly to Section 4 after seeing Figures 3 and 4.**

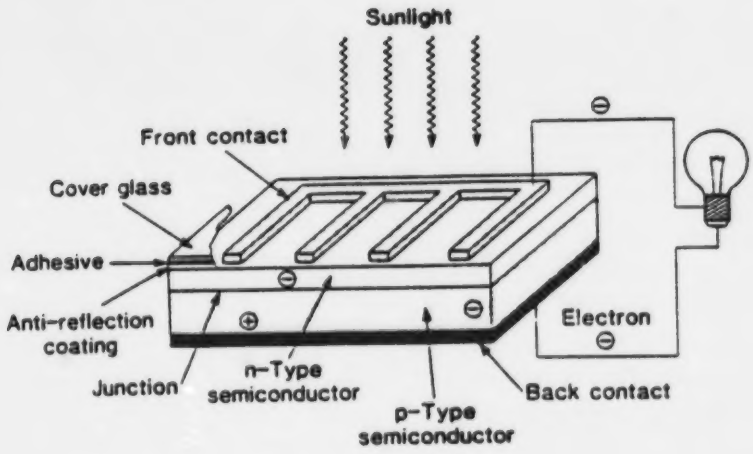


FIGURE 1 Operation of a photovoltaic cell. When light is absorbed by a semiconductor, electrons and holes are created, which can move through the semiconductor material. The semiconductor junction provides a charge separation mechanism: electrons move to the n side of the junction, and holes to the p side. When contact is made to the front and back surfaces of the cell, a current flows, which can be used to power electrical devices. After Reference 23.

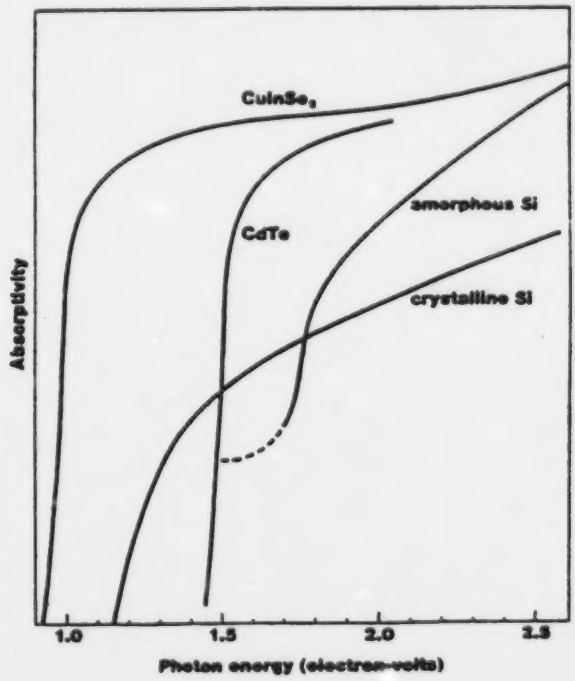


FIGURE 2 Optical absorption by thin film materials. After Baer [11].

The photovoltaic effect is a result of three basic processes [8,21]: (1) absorption of solar radiation by the cell resulting in the formation of mobile charge carriers in the material, i.e., electron-hole pairs, (2) the electron-hole pairs generated by the light must be separated and collected, otherwise they would eventually recombine to produce heat rather than electricity and (3) charge carriers must diffuse from where they are created by the light to the charge separation region, i.e., the p-n junction.

Solar cells must be thick enough to absorb a large fraction of the light falling on its surface. The thickness of the semiconductor material in a solar cell is inversely proportional to the absorption coefficient of the material (see Figure 2). Crystalline silicon, for example, has a relatively small absorption coefficient and thick wafers (greater than 100 microns) are required to make efficient solar cells. Gallium arsenide, in contrast, has a large absorption coefficient, and only a one micron layer is required to absorb most of the light falling on its surface.

The efficiency of solar cells depends on a large part on the energy bandgap of the semiconductor material that absorbs the incoming light (see Figure 3). By far, the greatest loss in efficiency of solar cells is due to the mismatch between the solar radiation arriving at the earth's surface and the energy gap of the semiconductor material used to manufacture the solar cell [27]. Incoming light with energy less than the energy gap of the material cannot create electron-hole pairs and thus cannot contribute to the photocurrent. Light with energy greater than the bandgap is absorbed (creating electron-hole pairs which can be collected by the p-n junction), but the energy in excess of the bandgap is quickly lost and converted to heat. These intrinsic loss mechanisms are the major reason why single-junction solar cells have theoretical efficiencies of only ~ 30% for unconcentrated sunlight.

Electron-hole pairs generated by the light are separated in solar cells by the electric field which is built into the device by the formation of the p-n junction. The strength of this field is determined by the energy bandgap of the semiconductor materials. The open circuit voltage of the cell and, hence, the conversion efficiency of the cell also depends of the the magnitude of the electrical potential at the p-n junction.

Separation and collection of the photo-generated electron-hole pairs will not occur in the solar cell unless the charge carriers are able to reach the p-n junction before they recombine. Therefore, the lifetime of the charge carriers must be long enough so that they can diffuse to the junction and be collected by the metallic electrodes. This, to some extent, explains the extremely high purity silicon which is required to make very efficient crystalline-silicon solar cells. Crystalline silicon is a poor absorber of light, therefore, charge carriers can be created at relatively large distances from the junction. In order for these charge carriers to be collected they must thus diffuse a significant distance. Impurities and crystal imperfections

increase the electron-hole recombination rate thus reducing carrier lifetimes and decreasing cell efficiency.

Recombination of electron-hole pairs decreases the efficiencies of solar cells. Radiative recombination of electron-hole pairs will always occur in solar cells [8,27]. This is an intrinsic loss which cannot be eliminated. However, other recombination processes which are caused by impurities or defects in the material or which occur at the surfaces of the cells can be eliminated by careful design and manufacture of the solar cell. For example, passivation of the surface of the silicon cell with a layer of SiO_x reduces surface recombination rates and increases cell efficiencies [28-30].

The maximum theoretical conversion efficiencies of single-junction solar cells (for AM1.5 sunlight) are calculated to be: (1) ~ 31% at 1 sun intensity and (2) ~ 37% at 1000 suns concentration [27]. These conversion efficiencies are for an ideal semiconductor with an energy bandgap of 1.35 eV. Efficiencies will be lower for other semiconductor materials. Moreover, only radiative recombination losses are included in these calculations. Practical efficiencies could be significantly lower, depending on the semiconductor material.

The inability of a single-junction solar cell to respond to the complete solar spectrum has led to the concept of multi-junction or tandem solar cells [9-11,27,31]. The concept is simple and is illustrated in Figure 4: stack two or more solar cells (made of materials with different energy gaps) on top of each other and use the light passing through the top cell in the lower cells. Since the tandem cell responds to a wider range of the solar spectrum these cells should be more efficient than single-junction cells. Of course, the additional power provided by tandem cells must be worth the extra cost of making them. The high BOS area-related costs presently give a large economic advantage to high-efficiency solar cells.

Henry [27] has calculated the theoretical efficiency of an ideal two-junction solar cell. For 1000 suns, the calculated efficiency (AM1.5 and 27°C) is 50% and we estimate that it would be 42% under 1 sun. The efficiency of a-Si tandem cells is much less than the efficiency of an ideal solar cell. Fan and Palm [31] have calculated the conversion efficiencies of single-junction and two-junction a-Si solar cells. At 1 sun, the theoretical efficiencies are 15% for single-junction cells and 19-20% for two-cell tandem structures. (Practical efficiencies are ~15% lower.) In the optimal tandem cell, the top and bottom cells have bandgaps of 1.85 and 1.35 eV, respectively.

The theoretical efficiencies of solar cells are reduced by extrinsic loss-mechanisms, e.g. reflection, shading, nonradiative recombination and surface recombination [27,32]. Extrinsic losses could, in theory, be eliminated by improving both the design of the solar cell or the quality of the semiconductor material. For example. reflective losses are essentially

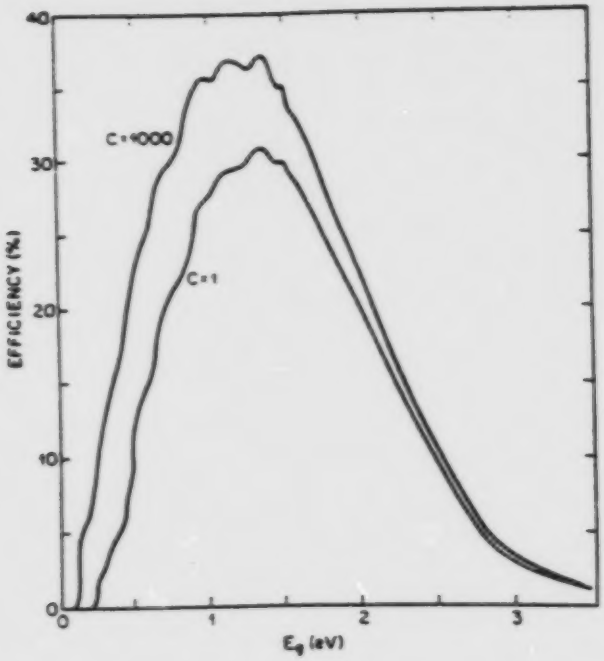


FIGURE 3 Theoretical solar-cell efficiency versus energy gap for solar concentrations of 1 and 1000 suns. After Henry [27].

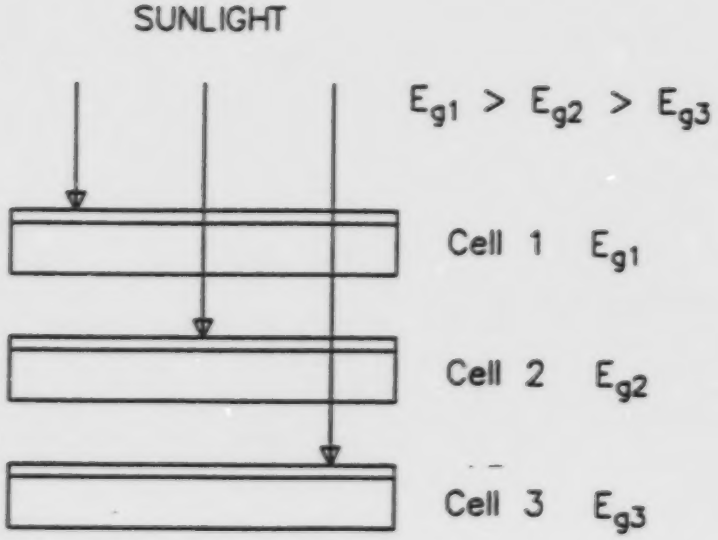


FIGURE 4 Multijunction (tandem) cells capture a larger portion of incident radiation than do single-junction cells.

eliminated by using a double layer antireflection coating and by texturizing the top surface of the cell. The improvement in cell efficiency, produced by reducing extrinsic losses, must warrant the added cost. This is an economical question rather than a basic physics question.

4. PHOTOVOLTAIC CELL/MODULE TECHNOLOGY

4.1 SINGLE-CRYSTAL SILICON SOLAR CELLS

Single-crystal silicon solar cells are manufactured by forming a p-n junction on silicon wafers (100 to 250 microns thick) using gaseous (phosphorus) diffusion techniques. The silicon wafers (p-type) themselves are cut from single-crystal silicon ingots manufactured using the Czochralski (CZ) growth method. Much of the expensive semiconductor-grade silicon is wasted in the saving process. Nevertheless, this is, currently, the best known and most economical method for manufacturing single-crystal silicon cells.

Production cells made from CZ ingots have efficiencies of ~14% (module efficiencies of ~11%) and research-grade CZ cells have reached efficiencies of 17 - 18% [28]. More efficient solar cells can be made using floating-zone (FZ) silicon wafers. Conversion efficiencies up to 19% have been attained in the laboratory for FZ silicon cells [28]. However, these solar cells are still too expensive for terrestrial applications.

Single-crystal silicon cells can be purchased in large lots for ~ $5.0/Wp. (This price has remained fairly constant over the last 3 years [14].) The price is high because the processing of metallurgical grade silicon ($1.4/kg) into high-purity silicon (~ $50/kg) is involved and expensive, a large amount of silicon is needed to make the cells, silicon is wasted in the saving process, and the technology is not easily automated. In fact, the cost of the single-crystal silicon wafers alone accounts for ~ 60% of the total module cost. Although the cost of crystalline-silicon solar cells has decreased by a factor of ten within the last decade, further dramatic cost reductions will be difficult.

Nevertheless, PV modules made of single-crystal silicon solar cells dominate the current (non-consumer) PV market. The technology is well established, the modules are reliable (guaranteed for 10 years) and there are no major technological barriers to overcome, i.e., the fundamentals are well known. Moreover, the advances required to produce cheaper cells, which are required for the widespread adoption of PV power systems, are well documented: cheaper semiconductor-grade silicon, faster growth rates for silicon ingots, larger ingots, and more efficient saving.

Significant progress has been made in the past decade in reducing module costs and increasing module efficiencies. For example, increases in ingot diameters has made possible the use of square solar cells (made from

circular cells by cutting off four sides) in PV modules. This increases the packing density of solar cells in modules and hence the module efficiency. However, progress in reducing the cost of single-crystal solar cells will be more difficult in the future. Economical analysis of PV power generation shows, for example, that highly-efficient solar cells are needed to reduce system costs [18,28,33]. These cells can only be made using semiconductor-grade silicon. Thus, the hopes for significant cost reductions resulting from use of "solar" grade silicon [34], which is less pure than semiconductor-grade silicon, do not now seem credible.

ARCO Solar is the world's largest manufacturer of single-crystal silicon PV modules. However, it does not intend to increase its present production capacity [35]. ARCO Solar is spending its R&D funds to develop high-efficiency tandem solar cells based on a-Si:H and $CuInSe_2$ thin-film technologies [10,11,35]. ARCO Solar obviously feels that thin-film solar cells will be the technology choice of the future. The advantages of this technology are obvious, i.e., smaller quantities of high purity materials are needed, and automated production of modules is possible.

Recently, exciting advances [36-40] in crystal-silicon solar cells for use in concentrator systems have been announced. In these systems, optical components are used to focus sunlight onto a small cell. These systems are economically viable if the cost of the tracking and optical components (per unit area) is much less than the cost of solar cells. In addition, since fewer solar cells are required to generate the same amount of power, they can be more expensive than flat-plate solar cells. Thus more elaborate methods can be used to manufacture these cells.

Researchers at Stanford [38] have now developed solar cells with efficiencies up to 27.5% for concentrated (500 suns) sunlight. These solar cells do not have planar p-n junction and expensive integrated circuit technology is required to manufacture them. The only remaining uncertainties are the cost of making thousands of these cells and the efficiencies of mass produced cells. The Electric Power Research Institute (EPRI) is now investing a significant amount of funds to determine these parameters [39].

Unfortunately, for Canada, concentrating systems are only viable [18,33] in locations with high insolation levels and where the direct component of the sunlight represents a large fraction of the total available solar energy (concentrator systems cannot focus diffuse light), that is, the sky must be clear most of the time. These conditions are rarely found in Canada. Even locations in Florida are not suitable for concentrator technology [18] because of adverse weather conditions. Thus, the Canadian PV research budget should not be used to support R&D in concentrator cell and module technologies.

We do not see much potential for spin-off benefits from R&D on single-crystal silicon solar cells. Much of the silicon technology is driven by the

needs of the semiconductor industry, which is ~ 100 times larger than the PV industry in terms of silicon usage. The need for large scale integration, for example, is creating a need for large diameter silicon wafers. These wafers can also be used to manufacture solar cells. Canada, however, does not nov have the facilities to produce silicon ingots. Therefore, the investment required to build this industry would be quite large. It is doubtful that such an investment would be viable. More impact would be obtained by spending investment and R&D funds on emerging technologies such as GaAs semiconductor devices and/or a-Si devices where Canada can be in the forefront of research and development by spending relatively small amounts of money.

Finally, it has been stated that Canada could benefit from the PV revolution by supplying semiconductor grade silicon to the rest of the world. However, although Canada exports metallurgical grade silicon, it does not nov produce semiconductor grade silicon. Today, the semiconductor industry uses 100 times more silicon than the PV industry. Why isn't Canada the world's supplier of purified silicon for the semiconductor industry? Obviously, a cheap energy supply is not sufficient to give Canada an edge in the production of relatively small amounts (compared to aluminum ingot production) of semiconductor-grade silicon. Moreover, if a-Si solar cells do become the technology choice of the future, the silicon requirements of the PV industry will be substantially reduced. It is too late for Canada to invest funds in the production of semiconductor-grade silicon or single-crystal silicon ingots.

4.2 POLYCRYSTALLINE AND RIBBON SILICON TECHNOLOGIES

In an effort to reduce the cost of silicon solar cells, the development of polycrystalline and ribbon silicon technologies have been pursued. In fact, some U.S., e.g., Solarex, and European companies, e.g., Siemens, have been concentrating their efforts on the production of polycrystalline silicon solar cells. It is thought that this technology will be a strong competitor to the emerging a-Si technology [41].

Polycrystalline silicon differs physically from single-crystal silicon in that it is composed of many individual grains of single-crystal silicon. The size and quality of the grains determine the efficiency of polycrystalline silicon solar cells. The presence of grain boundaries limits the efficiency of the solar cells. The average efficiencies of these type of solar cells is ~11%.

Polycrystalline silicon is commercially produced by casting molten silicon into square ingots. The cost advantages over single-crystal silicon technology are derived from: (1) increased throughput because casting of ingots is faster than growth of ingots using the Czochralski method. Thus, the number of wafers produced per dollar invested in the production facilities is increased. (2) Energy costs are reduced. (3) Modules are more efficient because the cell packing factor with square cells is higher than with circular cells. This latter advantage is less important nov that ARCO Solar is marketing its

new square-cell silicon modules [42]. The wastage of silicon material due to saving still remains in the production of polycrystalline solar cells.

A big disadvantage of the polycrystalline material is that very efficient (more than 15%) cells may not be possible with this material unless special techniques are used to passivate the grain boundaries and/or the surface of the cell [28-30]. The grain boundaries in the material increase the electron-hole recombination rates thereby reducing cell efficiency. However, if the balance-of-system costs are low, polycrystalline solar cells could be the technology choice in the coming years, especially if the problems associated with thin film technologies are not resolved. As with single-crystal silicon technology, there are no fundamental problems to be resolved and only economic barriers prevent the widespread adoption of these PV cells.

Ribbon or sheet technologies, in which sheets of silicon are produced rather than ingots, have been introduced in an effort to eliminate the saving process, hence avoiding the wastage of expensive silicon material. Many of the ribbon technologies have not lived up to expectations. Only the dendritic web, edge-defined film growth (EFG) and low-angle growth technologies were being investigated in the last years of the DOE Flat Plate Module Program [28] administered by the Jet Propulsion Laboratory (JPL). The dendritic web growth process produces single-crystal material whereas the other ribbon growth technologies produce polycrystalline silicon material.

Silicon wafers produced using the dendritic ribbon technology have been used to make solar cells with efficiencies up to 17%. Thus, this silicon ribbon has the right material properties for producing efficient solar cells. However, low crystal growth rates are required to produce this good material. This low throughput, compared to the current ingot growth technologies, is the principal impediment to the economic feasibility of dendritic ribbon. Crystal growth rates must be increased [28] in order to reduce the price of dendritic-ribbon silicon.

The major limitations of EFG ribbon are the low growth rates and the poor quality of the ribbon material. Reaction of the molten silicon with the graphite dies produces SiC precipitates in the material. EFG ribbon produces solar cells with lower efficiencies (up to ~12%) than are possible with CZ wafers.

With termination of the JPL Flat Plate Module project, research in ribbon technology has been curtailed. Since there are no complementary technologies that require ribbon silicon material, the commercialization of the ribbon technologies does not look promising. The major questions remaining are: (1) How economically can high quality ribbon be grown under production conditions? and (2) Will the introduction of a-Si solar cells make ribbon technologies obsolete?

4.3 GALLIUM ARSENIDE SOLAR CELLS

Gallium arsenide is an excellent semiconductor material for solar cells. Since it has a high absorption coefficient, only thin layers (one micron) are required to absorb a large fraction of the light falling on its surface. Thin semiconductor layers are more resistant to radiation damage, thus GaAs solar cells are more suitable for space applications, where cost is not an important factor. In view of Canada's current interest is space exploration, R&D in GaAs PV cells may be appropriate at this time. This, of course, is outside EMR's mandate.

The energy bandgap of GaAs (1.45 eV) is almost optimal for making efficient solar cell. The theoretical efficiency of single-junction GaAs cells is 29% for 1 sun concentration and 36% for 1000 suns [27]. Efficiencies of up to 26% have been demonstrated for 753 suns [43]. In addition, the larger bandgap makes GaAs better suited than silicon for high temperature applications, e.g., concentrator solar cells, because the decrease in cell efficiency with increasing temperature is less pronounced for materials with large energy bandgaps.

The only drawback to the use of GaAs in PV terrestrial applications is its very high cost. Large area GaAs wafers are difficult to manufacture and very expensive [44] (about a factor of 30 more expensive than crystalline silicon wafers). Thus GaAs solar cells will not be used in terrestrial flat plate modules. GaAs solar cells should be viable in concentrator modules, where the added expense is justified by the increased efficiencies [43,45].

Gallium arsenide is a high technology semiconductor material. One of the technological problems limiting its widespread use in the semiconductor industry is the expense required to make large, good quality crystals for integrated circuits. However, much effort is now being expended [44] to solve these problems since GaAs devices are 5 to 10 times faster than silicon devices and they consume 10 times less power.

The complementary R&D efforts in GaAs semiconductor devices for information processing will lead to advances in GaAs solar cells. For Canada, GaAs R&D is important. Bell Northern is at the leading edge of fibre optics technology so it needs GaAs semiconductor devices to remain a competitor in the fibre optic communications market. Much more importantly, the GaAs semiconductor industry is not very large. This gives Canada a chance to be part of this future growth industry without having to play catch-up with the rest of the world. The collaborative efforts in this field between Bell Northern and the National Research Council [44] should be strongly encouraged.

Unfortunately, GaAs research cannot be justified in terms of PV development alone. GaAs is too expensive to be used in flat plate modules and concentrator modules are not viable in Canada because of its geographical

location and weather patterns [18].

Canada could also benefit from GaAs technology as a supplier of gallium (found with zinc ores) or even GaAs crystalline wafers. In fact, Cominco, a large Canadian mining company, is Canada's only producer of GaAs CZ wafers [44]. However, Canada must act quickly since Rhone-Poulenc Minerale Fine of France is already planning to increase its production of high-purity gallium with the addition of two new plants by the end of 1988 [46].

4.4 THIN FILM TECHNOLOGIES

Companies such as ARCO Solar can nov produce solar modules containing crystalline silicon wafer cells for $5-10/Wp. The cost is mainly in the silicon material, which is made by the CZ process from a starting material of 99.9999% pure polycrystalline silicon. High-purity polysilicon costs ~$55/kg and 1 kg of polysilicon makes roughly 30 wafer cells (~$2/Wp for the silicon material alone). Furthermore, the CZ process is very energy intensive. The costs of the silicon material and the CZ manufacturing process, together with the costs of wafer cutting and junction formation, account for ~ 60% of the costs of crystalline silicon solar modules.

From the above discussion, the advantages of thin-film technologies over wafer technologies are apparent. A key to the importance of certain thin-film materials is their high optical absorption coefficient (see Fig. 2). The optical absorption in the thin film materials considered in this report (a-Si, CdTe, and $CuInSe_2$) can be more than 100 times greater than in crystalline silicon. Instead of requiring an active thickness of 300 μm, as in crystalline silicon cells, a thin-film solar cell may be only 1 μm thick. Moreover, no sawing or etching is required, and junction formation is an integral part of the thin-film deposition procedure. Furthermore, thin films may be deposited in a fully-automated continuous process onto various substrates. Thus, photovoltaic power for less than $1/Wp depends on the use of thin films.

To quote Glaser [47]: "Thin film materials and technologies will become dominant. Efficiencies in the 15-20% range and long-term stability with reproducible parameters will be achieved during the next decade and large areas of thin film solar cells will be mass produced. Eventually multiple bandgap solar cells employing several different materials will reach efficiencies of around 30% and will provide a significant impetus to the rapid penetration of photovoltaic systems for both decentralized and centralized applications."

4.4.1 Amorphous Silicon and Related Alloys

One conclusion of this study is that amorphous silicon and its alloys is the thin-film technology of greatest importance. This is in full recognition of the current and projected efficiencies of all three major thin-film technologies, which are quite comparable at present. Amorphous silicon is by far the best understood of these materials, and is also superior from the point of view of long-term reliability, safety, and sources of supply. That is, there are no resource constraints with silicon, and pollutants such as Cd, Se, and As are avoided. In addition, the potential costs and efficiencies of a-Si cells in the long term are at least as favourable and in most cases considerably better than those of the other thin-film technologies.

Perhaps one of the most important features of a-Si thin films which is not shared by the other thin-film materials (CdTe and $CuInSe_2$) is the flexibility with which the electrical and optical properties of the material can be controlled. Amorphous silicon can be doped either p-type or n-type and the doping concentrations may be adjusted over a wide range. This property is not enjoyed by the other materials, which cannot easily be doped by extrinsic means; their dopant type is controlled by stoichiometry.

In addition, the band gap of the a-Si film can be easily varied through compositional changes. By mixing tin or germanium into the gas ambient during deposition, the energy gap may be decreased; mixing nitrogen or carbon accomplishes the opposite effect. Heterojunctions and tandem cells can be prepared in a single deposition step, simply by controlling the gas flows and other relevant process parameters. It is for these reasons that we feel fairly confident that a-Si based solar cells will dominate the thin-film arena in the long term. DOE/SERI appears to share this view. They have subcontracted $18.6 million over three years in a-Si research (30% cost shared by industry) against only approximately $3 million/year in all the other principal thin-film materials combined [48,49].

We also believe, however, that the overriding advantage of amorphous silicon materials is their wide range of additional applications, many of which have already been commercially realized. Selected examples from optoelectronics and microelectronics are discussed later in this section. The potential for spinoffs from R&D in amorphous silicon is phenomenal, a property not shared by the other thin-film technologies to any comparable degree. It is even conceivable that amorphous silicon materials could become a mainstream technology in ultra-large scale integration [50].

4.4.1.1 Properties of Amorphous Silicon

A chronology of developments in (hydrogenated) amorphous silicon is given by Takahaski and Konagai [9]. This spans the period from 1965 to 1982. The breakthrough with this material came with the realization that incorporation of

hydrogen into amorphous silicon, as introduced in glow discharges in SiH_4, reduced by orders of magnitude the number of silicon dangling bonds. This allows the formation of p- and n- type amorphous silicon by doping. The hydrogen content, typically 15%, also increases carrier lifetime, due to the removal of the defect states associated with dangling bonds and increases the energy gap.

A comparison between crystalline silicon and a-Si:H reveals the following important differences. The energy gap of crystalline silicon is approximately 1.1 eV, whereas that of a-Si:H is typically 1.6 to 1.8 eV, depending upon the hydrogen content. The minority carrier diffusion length is typically 10-100 μm in crystalline silicon, but only 0.1-2 μm in a-Si. The optical absorption coefficient above the bandgap energy is larger by approximately an order of magnitude for amorphous silicon (see Figure 2).

Recent progress with amorphous silicon cells have been revieved by Hamakawa [6,51] and predictions for the future have been advanced by Carlson [52]. Fabrication of high-performance cells is described by Nakano et al [53] and Arya et al [54].

4.4.1.2 Device Structures and Cell/Module Manufacturing Processes

There are basically two classes of a-Si solar cells to be discussed: single-junction cells and multijunction cells. We discuss the latter category primarily under recent developments. The majority of the multijunction work is aimed at two-junction or tandem cells; within this category there are 2-terminal and 4-terminal versions.

Single-junction cells which hold the greatest promise for high efficiency are the so-called p-i-n cells, named for their doping distribution. These are generally of the type shown in Figure 5. The p-layer is usually an a-SiC:H alloy which has a large energy gap and serves as the window layer. This improves the short wavelength response of the cell by removing the surface-region absorption and is responsible for the large value of short-circuit current [55]. Another important enhancement is the use of boron to remove the residual n-type doping of the intrinsic layer [56]. This increases the electric field, thereby enhancing the efficiency, and reduces instabilities associated with the Staebler-Wronski effect [57] (see below).

The effects of module design upon the performance of a-Si cells has been investigated by Morel et al [58] at ARCO Solar. Net efficiencies were found to be well below the gross efficiencies of the devices themselves. The amorphous silicon cells are generally incorporated into modules in the manner indicated in Figure 6 [59]. This approach minimizes the effects of series resistance (by employing wide and short cells), and produces high module voltages by connecting the cells in series.

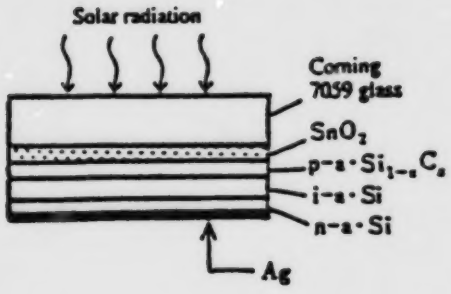


FIGURE 5 Structure of a p(SiC)-i-n solar cell. Figure from Takahashi and Konagai [9].

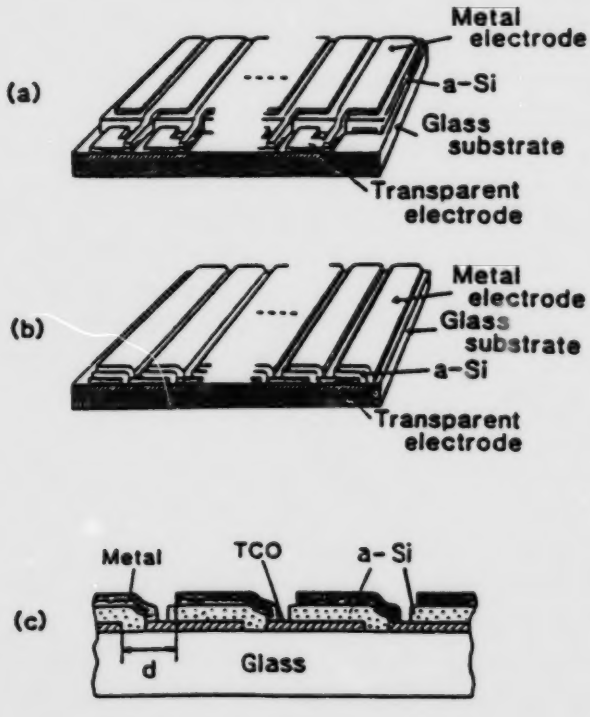


FIGURE 6 Construction and cross-section of integrated-type a-Si:H based solar cell submodule: (a) Type I, (b) Type II, (c) Cross-section of Type II cell connection, d is the distance for cell connection. After Nakano et al [59].

The efficiencies of single-junction cells will probably reach their maximum practical values of approximately 15% (large area) in 5 years. For the longer term and larger improvements, we must look to tandem cells.

4.4.1.3 Recent Developments: Tandem Cells and Other Improvements

Tandem cells have the potential for considerably higher efficiencies than single-junction devices. The maximum efficiency of a single-junction amorphous silicon cell with E_g = 1.7 eV is theoretically 18.7%, but with two junctions it can be up to 27% [7,31], since tandem cells are better matched to the solar spectrum. These predictions depend upon having a 4-terminal tandem cell, in which the separate cells are independently contacted. In the case of 2-terminal tandem cells, the currents in the two cells must be equal and this constrains the maximum possible efficiencies. The efficiency of the 2-terminal cell is more sensitive [31] to variations in energy gap, operating temperature and solar spectrum (i.e., air mass and weather conditions).

For the tandem cells in which the additional cell is made from a larger band gap material (than a-Si:H) the best choices are a-SiN:H or a-SiC:H. For smaller band gap materials SiGe:H and SiSn:H are under development [60,61]. Madan [7] quotes efficiencies in excess of 12% for laboratory tandem cells from both Osaka University in Japan and Energy Conversion Devices (ECD) in the United States. The DOE/SERI goals for 1988 [48] are: (1) 13% for 1 cm^2 single-junctions cells and (2) 18% for 1 cm^2 tandem cells. ECD together with Solarex and ARCO Solar expect 15-18% efficiency from tandem cells in the near future [12]. ARCO Solar has already obtained 12% efficiency in small area a-Si/$CuInSe_2$ cells [11].

Recent advances in deposition of a-Si films by chemical vapour deposition [62], and in the deposition of a-Si alloys such as a-SiN:H [63], a-SiGe:H [64], and a-SiSn:H [65] convince us that all-amorphous silicon based tandem solar cells of respectable efficiency (18-20%) are achievable in the not too distant future (perhaps 10 years). A somewhat different conclusion, more pessimitic with respect to tandem cells as opposed to single-junction devices, was expressed by Rothwarf [66].

4.4.1.4 Technological Barriers: Stability and the Staebler-Wronski Effect

When a-Si solar cells are exposed to sunlight for a long period of time, there is a noticeable decrease in the conversion efficiency of the cell. Single-junction cells, for example, can lose up to 50% of their initial efficiency. This is called the Staebler-Wronski effect after the workers at RCA who first studied the problem [57]. Recovery from this degradation can be induced by heating the samples at temperatures as low as 150°C. The degree of deterioration is sample-dependent and is reduced for cells having higher electric fields in the intrinsic layers. Thus, cells with thinner

i-layers are more immune to this degradation because they promote higher electric fields.

The current understanding of the Staebler-Wronski effect is not complete, but they are thought to arise due to formation of trapping centers by the illumination. Weak three-centre Si-H-Si bonds appear to shift to Si-H bonds, leaving unsatisfied bonds which produce the trapping centre. In operation, these traps capture charge which distorts the electric field profile. This in turn reduces the field and, thus, the collection efficiency of the photogenerated carriers [67].

The good news is that with proper design of the cells, more and more groups are successful at eliminating the Staebler-Wronski effect from their devices. Degradation-free devices based upon tandem junctions have been reported by the Japanese as well as by ECD [68,69]. The ECD cells incorporate fluorine into the amorphous silicon but the Japanese workers obtain similar stability without fluorine [9, Sec. 6.4]. Profiling of the boron concentration in the i-layer has also been shown [56,70] to improve carrier collection and cell efficiencies. It seems that a good design is one which keeps the electric field as large as possible in the intrinsic layer (where the most of the light is absorbed) [71,72] and minimizes the impurities in this region.

4.4.1.5 Economics and Spinoffs

Amorphous silicon-based thin-film solar cells have considerable potential for further cost reductions. In particular, there are several ways to increase the deposition rate without affecting the electronic properties of the films. The deposition rate has a direct impact on the cost of cells. If the deposition rate is doubled only one half the number of fabrication plants are needed to fabricate a given number of devices per year. Moreover, the fabrication technology is also compatible with scaled-up automated continuous production.

Among the methods which have shown promise in increasing the deposition rates are the use of Si_2H_6 rather than SiH_4 as the reactant gas. Deposition rates may be increased from 0.3 nm/s to 2.0 nm/s in this manner [9, Sec. 6.3]. Another potentially more important route to higher deposition rates (while maintaining film quality) is the use of microwave plasmas rather than radio-frequency plasmas in dissociating the SiH_4 gas [73].

Dickson et al [74] have experimented with a single chamber load-locked process for the deposition of amorphous silicon with high throughput. One of the interesting results of their study was the way in which efficiencies varied with the areas of the cells. For a very small area cell (0.265 cm^2), the efficiency was 10.4%, whereas for 420 cm^2 and 1000 cm^2 cells they observed efficiencies of 8.7% and 8.1%, respectively. It seems as though the major loss in efficiency with size occurs for relatively small devices.

In our opinion, the major economic consideration in favour of a Canadian R&D activity in amorphous silicon is the considerable potential for spinoffs in other areas of electronics, optics and computers. This material is proving to be one of the most versatile and interesting materials since crystalline silicon. It has the capacity for doping in both polarities, with orders of magnitude change in conductivity. In addition, it has the extra material freedom associated with the degree of incorporation of hydrogen and other elements such as C, N, O, Sn, and Ge. Furthermore, it lends itself to the fabrication of 'chips' of practically any conceivable size, in contrast with the size limits of crystalline wafers. Amorphous silicon and its alloys have already been exploited for the following applications in addition to photovoltaics [50,75]:

Thin-film transistors
Picosecond photodetectors
Switching arrays for liquid crystal displays
Xerography, laser printers, and electrophotography
Photosensors and imaging arrays
Optical modulators and optical integrated-circuit elements
Optical mass memories and archival storage
Fusible links for wafer scale integration
Next-generation very-large-scale-integration??

4.4.2 Other Thin Film Technologies

During the past five years or so, the emphasis on thin-film cells, other than a-Si cells, shifted away from copper sulphide (Cu_2S) to polycrystalline cadmium telluride (CdTe) and copper indium diselenide ($CuInSe_2$). These cells employ CdS or CdZnS layers as well, but the CdTe and the $CuInSe_2$ provide the active photovoltaic regions. Cu_2S turned out to have insurmountable stability problems.

Zweibel et al [49] report that the DOE/SERI program in polycrystalline thin films aims to develop single-junction cell efficiencies of 15% at a cost of $\$50/m^2$ with both CdTe and $CuInSe_2$. In addition DOE/SERI is interested in tandem cells with CdTe over $CuInSe_2$, with potential efficiencies in excess of 20%, at costs of around $\$75/m^2$. Among the most important concerns with these materials are: (1) efficiency, (2) cell area, and (3) stability. In general the fabrication techniques do not scale as gracefully to large areas as they do for amorphous silicon, although CdTe is much better than $CuInSe_2$ in this respect. Efficiencies, as a function of cell area, are shown in detail in the paper of Zweibel et al [49].

4.4.2.1 Cadmium Telluride: Principles and Processes

One major advantage of CdTe over $CuInSe_2$ is the variety of fabrication methods available to make large-area cells of respectable efficiency. These methods include screen printing/sintering, electrodeposition, close-spaced sublimination, chemical vapor deposition and spray pyrolysis. Mitchell et al [76], for example, have investigated high rate CdTe deposition by close space vapour transport to obtain over 10% efficiency in small areas. Matsumoto et al [77], on the other hand, have prepared screen-printed small-area CdTe cells with efficiencies up to 12.8%

CdTe cells are typically constructed by deposition of CdTe films onto a CdS layer. The opposite order of deposition is also possible. The successful fabrication of a properly-operating cell requires a poorly understood heat treatment, apparently to cause carrier-type conversion. Bube et al [78] have carried out a careful study of CdTe films and solar cells prepared by closed space vapour transport and hot wall vacuum evaporation. The material as deposited was found to be p-type. Doping is due either to native defects associated with Cd vacancies or to diffusion from the graphite substrate. The efficiency of the cell is limited by the resistance associated with the contacts to the p-type CdTe.

The highest efficiency obtained over reasonably large areas with an all-thin film process (closed space vapour transport) is 10.5% but screen printing and electrodeposition have also given efficiencies of 9% and 8%, respectively [78]. This is very promising; however, the difficulties with dopant control are a bottleneck to much further progress with this material. Contacting is only successful on exposed CdTe surfaces, where either etching or annealing Cu-containing graphite paste applied to the surface makes CdTe more p-type. This requires using inverted structures of glass/SnO_2/CdS/CdTe/contact to obtain 10% efficiency. Chu et al [79] managed to get 8.2% in noninverted cells.

The band gap of CdTe is 1.4 eV, which should provide the optimum conversion efficiency. The CdS layer acts as the high band gap layer in the heterojunction cell, but since its energy gap is only 2.4 eV, it blocks some of the solar radiation. ZnO and CdO, with energy gaps of 3.3 eV and 2.6 eV, respectively, are being explored as replacements for the CdS window layer. However, oxygen does have drastic effects on the performance of CdTe devices [80]. Therefore, the deposition parameters must be carefully controlled.

4.4.2.2 Copper Indium Diselenide: Principles and Processes

On the basis of results reported in the literature so far, it is probably a safe statement that $CuInSe_2$ is the second contender after amorphous silicon. The analyses and outlooks presented by Hermann et al [81] and Zweibel et al [49] are instructive in arriving at this conclusion. Fabrication methods that produce high-efficiency $CuInSe_2$ cells are vacuum co-evaporation and

magnetron sputtering. The prescribed method for making these cells involves heat treatments in air or oxygen at 150-200°C for an hour or so, which doubles the cell efficiency by increasing the cell voltage and the fill factor. The mechanisms for this behaviour are currently under study at SERI, but there remain many unansvered questions.

Among the more promising new approaches to the deposition of $CuInSe_2$ are the reactive sputtering method described by Thornton et al [82], who produced stoichiometric films with respectable efficiencies (4%). Shing et al [83] at ARCO Solar have been able to obtain extrinsic doping of $CuInSe_2$ using phosphorus to convert from n-type to p-type doping. This work was done with single crystals but should be extendable to thin films. Studies of the contacts and metallization systems for $CuInSe_2$ have been carried out by Kapur et al [84] who conclude that in-diffusion of metals and oxidation of electrodes can affect reliability and process-sensitivity.

The energy gap of $CuInSe_2$ is only 1.0 eV. This limits its theoretical conversion efficiency considerably as compared to CdTe. It is however, the most light absorbing material known in the solar wavelength range (see Figure 2), and 99% of the visible light from the sun is absorbed within 0.5 μm. It also exhibits a respectable carrier lifetime and the combination of these factors gives it an excellent collection efficiency. In the long term, $CuInSe_2$ may become an excellent lover-layer cell in tandem cells, with amorphous silicon or CdTe as the upper cell. ARCO Solar has already obtained 12.5% efficiency with an a-Si/$CuInSe_2$ tandem cell. Two-junction cells with $CuInSe_2$ as the lover (small bandgap) layer are probably capable of 22% efficiency, whereas single-layer $CuInSe_2$ cells are limited to around 15% [49]. Boeing has already reported 11.9% efficiency for a 1 cm^2 $CuInSe_2$ cell [85].

Other investigations of $CuInSe_2$ of special importance include the detailed processing investigation by Birkmire et al [86] to examine the sensitivity to process parameters. Meakin et al [87] have studied the tandem combination CdHgTe/$CuInSe_2$ and they believe that this system has the ability to meet the long-term cost and efficiency goals for thin-film photovoltaics. The work at ARCO Solar as reported, for example, by Eberspacher et al [88] maintains that a-Si/$CuInSe_2$ tandem cells have the greatest potential.

4.4.2.3 Recent Developments

In the case of CdTe cells, the recent successful attempt at extrinsic doping [79], and the resultant achievement of over 8% in a noninverted cells are of importance. It appears that CdTe cells are well below their theoretical limits based upon the 1.4 eV band gap, and any progress in material control or basic understanding is potentially significant.

Basol et al [89] have shown that the limitations of CdTe due to series resistance can be alleviated by replacing CdTe by HgCdTe. This reduces both the bulk resistance and the contact resistance. Moreover, this can also be used to control the energy gap since CdTe has an energy gap of approximately 1.45 eV, whereas with 15% mercury the energy gap of HgCdTe decreases to 1.2 eV. This is potentially important for tandem cells.

Matsumoto et al [77] have recently improved the results of CdTe fabricated by screen printing. An efficiency of 12.8% was reported by these workers for an active area of 0.78 cm^2. The improvements were attributed to better preparation conditions for the carbon electrode by adding a small amount of copper to this electrode.

With $CuInSe_2$ the maximum theoretical efficiencies are much lower for single-junction cells because the band gap is only 1.0 eV. The possibility has been suggested however that this bandgap may be appreciably enhanced by incorporating Ga into the material. Noufi et al [90] have recently studied $CuGaSe_2$ films (energy gap of 1.68 eV) and have fabricated $CdS/CuGaSe_2$ solar cells. These cells exhibited an efficiency of 2.6%, which is a respectable first attempt. The theoretical efficiency of a tandem $CuGaSe_2/CuInSe_2$ cell is approximately 33%.

Recent reports [11] suggest that ARCO Solar has obtained 13.1% efficiency for laboratory devices (small size) and 7.1% for 1 ft^2 modules of a-$Si/CuInSe_2$ tandem cells. Also, in spite of the limited success with alternate fabrication processes, recently, 7% cells produced by electrodeposition have been reported by V. Kapur of Int. Solar Electric Technologies. In this process, copper is first electroplated onto a substrate followed by indium, then the surface is exposed to H_2Se. Electrodeposition, of course, holds out the promise of a large-area fabrication process for $CuInSe_2$ cells, which is presently one the primary limitation of this technology.

Birkmire et al [91] have proposed that the $CdTe/CuInSe_2$ tandem cell is a promising device and that it is realistically capable of 17% efficiency. Whether the $CuInSe_2$ is combined in a tandem cell with CdTe or with amorphous silicon, the long term benefits of exploring tandem cells seem to be apparent.

4.4.2.4 Technological Barriers

CdTe is an interesting photovoltaic material with an optimum theoretical energy gap of 1.4 eV. Whereas there are currently limitations on the voltage from $CuInSe_2$ cells, and stability issues with a-Si cells, CdTe is troubled by neither of these problems. Solar cells based upon CdTe or $CuInSe_2$ exhibit no apparent degradation from illumination alone. Nakano et al [53] have examined the stability of 118 CdTe modules in 3 countries over a period of 140 to 800 days. Only one module was unstable as a result of problems with waterproofing.

CdTe as a material does have other problems. The principal barrier to progress in CdTe is the control of contact properties and doping concentration (resistivity), and of the relation between the two. Dopants introduced into the material segregate at grain boundaries, or are inactive in the material for other unknown reasons. Post-deposition heat treatments in air employing ill-understood mechanisms are used to optimize these devices.

There are two barriers to further development of $CuInSe_2$ single-junction cells. One is the small energy gap which seems to be a fundamental limitation, with the proviso that it appears the energy gap may be increased with the addition of gallium. The other difficulty is that the attainment of respectable efficiency in this material (10% or so) presently relies on a delicate and poorly understood recipe involving several evaporation or sputtering steps that are not readily scaled to large area processes. This black magic may turn out to be unnecessary altogether based on the early reports of $CuInSe_2$ cells fabricated using electrodeposition methods.

The economic viability of CdTe and $CuInSe_2$ thin-film solar cells depends on the development of a fabrication process which is rapid (prepares large-area cells), involves simple equipment and is tolerant. It seems unlikely that any procedure based upon critical steps or "black magic" could be used in large-scale operation. CdTe is amenable to large scale production in the sense that there are several such methods which can produce decent PV cells. However, at the present time, the problems with doping and contacts make the process a critical one. Large-scale fabrication of $CuInSe_2$ has so far not been demonstrated, and the current processes require a degree of wizardry to obtain high efficiencies.

In short, the technologies of these materials are far less understood than that of amorphous silicon, and demand considerable basic research before their true potential becomes clear.

4.4.3 Forecasts for Thin Film Photovoltaics

In this section we present a summary of the predictions for efficiencies and cost of photovoltaic cells based upon thin films technologies. We consider only the major candidates: a-Si, CdTe and $CuInSe_2$. Figures 7 and 8 are a composite of present data, predictions by other industrialists, researchers, or agencies, and the conclusions of the present authors based upon this study.

Major sources of the predictions by others concerning cell efficiency and cost were Coutts et al [92], Barnett [93], Carlson [52], Hamakawa [94], Madan [7], Maycock [95], Wolf [96], Takahashi [97], Zweibel et al [49], Stone [98], Sabisky et al [48], Prince [99], Baer [11], Glaser [47], Gay [100], Lineback [12], Feucht [101], Fan [102], Meakin et al [87], and Mitchell et al [76]. Unless otherwise stated, a composite prediction from these workers is

marked 'others' in the figures below. They represent what, in the minds of the present authors, is the uniform optimistic party line of the photovoltaics industry. In our view, the end results are correct, but the time scale is overly optimistic. This is indicated by the predictions marked 'present study' below.

It is very difficult to distinguish between the future efficiencies of a-Si, CdTe, $CuInSe_2$ or indeed any other thin film technology that proves to be amenable to large-scale production techniques. The same remarks apply to cost. It is however an easy matter to distinguish the potential efficiencies of single junction and tandem cells, as shown in Figure 7. The curve marked 'tandem cells' in Figure 7 is intended to include all-amorphous silicon based cells as well as those incorporating the other thin film materials CdTe and/or $CuInSe_2$. Curves 3 and 4, which represent the predictions of others, include forecasts by SERI, Solarex, ARCO Solar, and ECD. The Japanese workers seem more reluctant to make predictions regarding the future of cell efficiencies. To be specific, the Japanese companies and some American companies such as ECD appear to be focussing on all-amorphous silicon devices, whereas ARCO Solar and SERI seem to hold out hope for hybrid tandem cells that incorporate $CuInSe_2$.

We have attempted (Figure 8) to distinguish between the future costs of amorphous silicon-only tandem cells, e.g., a-Si/a-SiGe and a-SiN/a-Si/a-SiGe, and tandem cells such as a-Si/$CuInSe_2$ or CdTe/$CuInSe_2$ which incorporate at least one device layer made from the polycrystalline materials. Our reason for making this distinction is our conviction that the large scale production processes will scale more favourably with amorphous silicon technology than with the other materials. We believe that the production of all a-Si tandem cells will remain a better understood and more controlled process with monotonic improvements in efficiency and cost.

4.4.4 Conclusions for Thin Film Solar Cells

On the basis of the discussion of the preceding sections, we draw the following conclusions regarding comparative materials and recommendations for Canadian R&D:

1. In the long term (after 1995 or so) the photovoltaics industry will be based on thin films and not on wafer or ribbon technologies.

2. The thin film materials of most promise are those based upon amorphous silicon and its alloys.

3. The other thin-film materials of importance to photovoltaics are $CuInSe_2$ and CdTe and related compounds. These materials are capable of similar efficiencies to those of amorphous silicon, but do not have the same flexibility in terms of tailoring the materials properties through composition. Furthermore, they do not appear to be as well understood or under comparable control during fabrication.

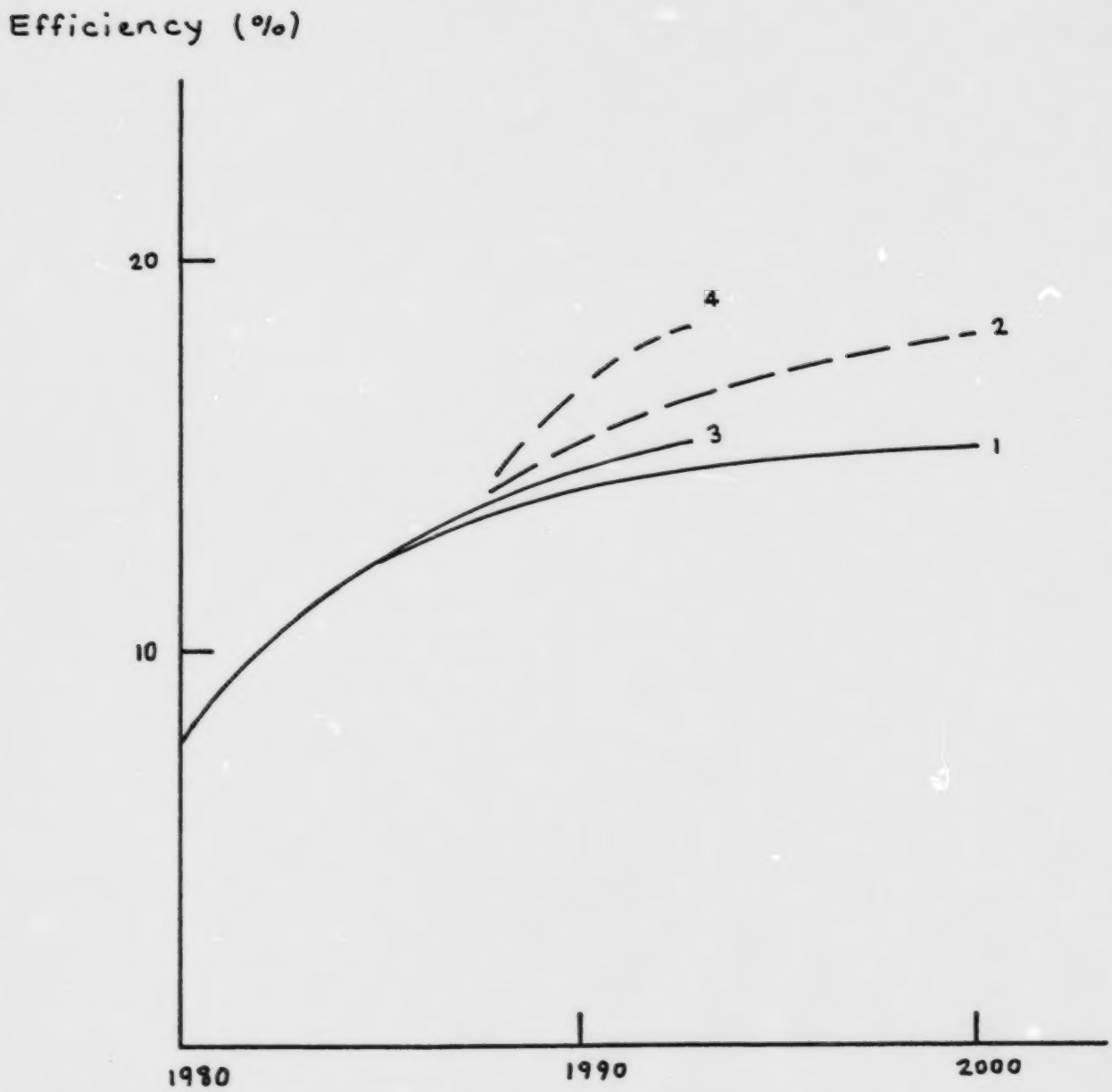


FIGURE 7 Module conversion efficiency of thin film solar cells (AM1 illumination). Solid lines: single-junction cells. Broken lines: tandem cells. 1, 2 This study. 3, 4 Others (see text)

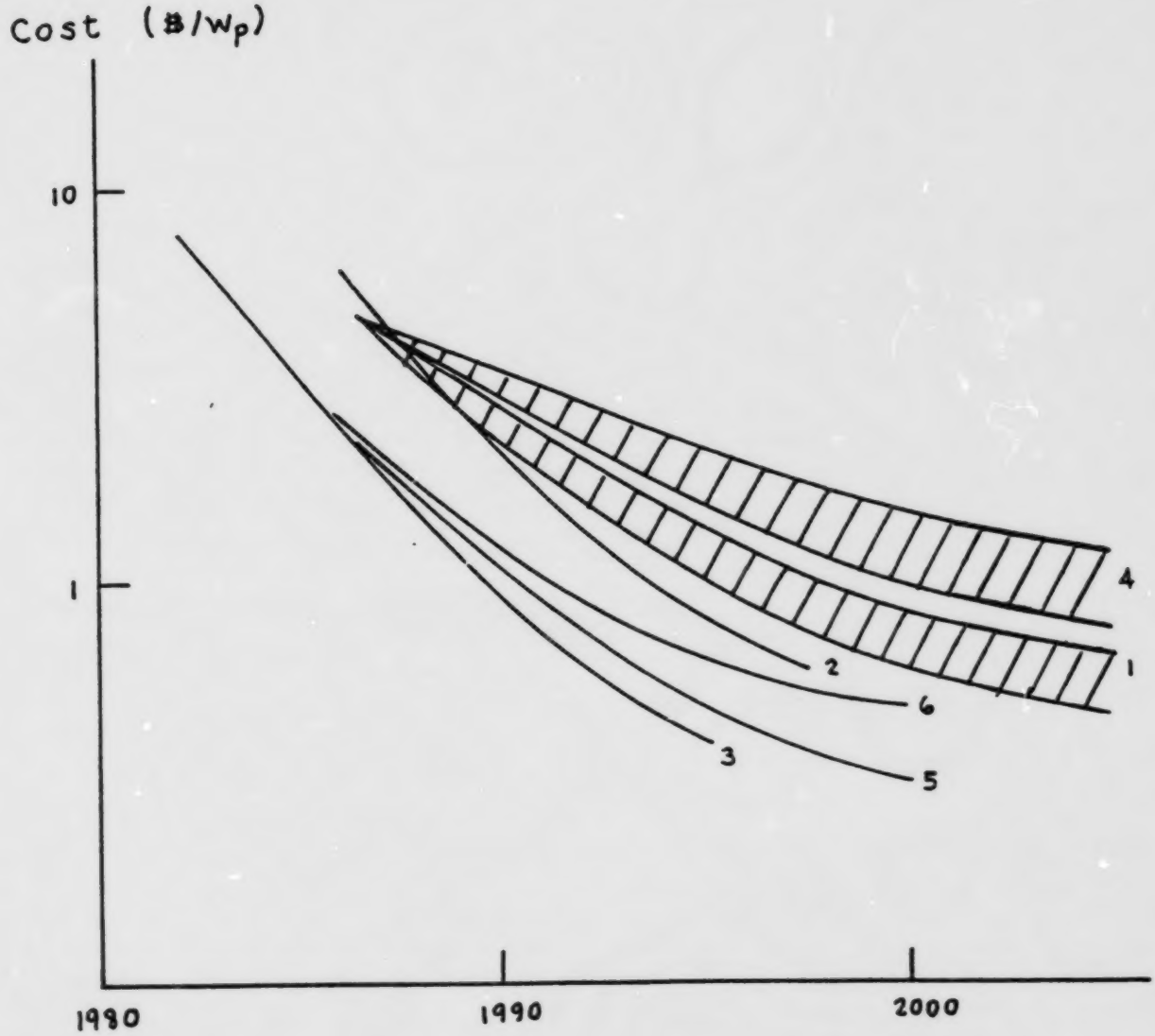


FIGURE 8 Cost of thin film photovoltaics ($1980 U.S./Wp). Amorphous silicon (tandem) cells: 1 This study, 2 Barnett [93], 3 Others. Cells employing CdTe or $CuInSe_2$: 4 This study, 5 Barnett [93], 6 Others (see text).

4. An R&D program in a-Si solar cells would have many spin-off applications. In fact spin-off opportunities in microelectronics, xerography, and electro-optical applications, appear to be far more promising commercially than photovoltaic applications.

5. The ultimate thin film solar cells will be tandem cells probably fabricated from amorphous silicon and its alloys such as a-SiGe:H and a-SiC:H. They may also include tandem cells incorporating layers of $CuInSe_2$ and/or CdTe, at least for many years to come.

6. The efficiencies of these tandem cells will reach 18% by the year 2000. This prediction contrasts with many others who believe this efficiency could be reached within 5 years.

7. The cost of amorphous silicon (tandem) cells will be less than $1/Wp by 2000. The ultimate cost could be as low as $0.40/Wp (perhaps by 2010) depending on market factors. The ultimate cost is not a technical issue.

5. BALANCE-OF-SYSTEM COMPONENTS

Balance-of-system (BOS) costs represent a significant fraction of the total cost of PV systems. The BOS costs are relatively higher for smaller PV systems. Therefore, BOS costs are important factors in determining the economic viability of PV systems. For PV applications at remote sites, for example, where the reliability of the PV system is of utmost importance in reducing operating and maintenance (O&M) costs, the energy storage subsystem, i.e. batteries, represents a large fraction of the system cost (more than module costs in some cases).

5.1 BOS AREA-RELATED COMPONENTS

BOS area-related components for a typical PV system, using flat-plate modules, would include [18] such items as: the array structure, foundations, sun-tracking equipment, land, and site installations (roads, fences, etc.). The BOS area-related components are low-technology items and no major breakthroughs are required for future cost reductions. However, there is not much experience in building large-scale PV installations and the possible economy-of-scale cost reductions are not well known. Careful design of the BOS area components will reduce system costs, installation costs and future O&M costs, and will increase the efficiency and reliability of the PV station.

Land costs vary widely from location to location. In general, land costs are highest near urban areas. Nevertheless, for PV utility stations, land prices do not represent a large fraction of the total BOS-area related costs. For example, at module efficiencies of 15%, a 100 MWp installation requires a

land area of approximately 2 km^2, if the average peak insolation level is 700 W/m^2 and the packing factor is 50% (twice as much land area as array area). At $1000 per acre (southern Ontario), the land for this installation only costs about half a million dollars. It should be noted that this station would only generate, on average, 20 MW of power assuming a capacity factor of 25% and BOS efficiencies of 80%.

For utility applications, BOS area-related costs, i.e., costs for the array structure and foundation (60%), site preparation (15%), module installation (15%), surge protection (7%), and land (2%), are an important factor in determining PV electricity costs [18]. The figures in parentheses indicate the relative importance of the various BOS-area components. Currently, BOS area-related costs represent ~50% of PV system costs. These high BOS costs mean that flat-plate modules with high conversion efficiencies are required to make PV power generation economically viable [18,28]. Nevertheless, even with high-efficiency modules, BOS area-related costs must be reduced to a minimum (less than $100/$m^2$) in order to make PV power competitive with power generated from coal stations.

ARCO Solar has demonstrated [103] at its Carrisa Plains PV station that sun-tracking equipment for flat-plate modules can increase the power output of the PV station by up to 40% compared to fixed arrays. The added cost of the sun-tracking equipment could be justified in terms of the additional power output of the station. It is thus important, for any location, to be able to determine the annual power generated by PV stations of various designs so that relative costs can be compared.

Consequently, models should be developed to simulate the power output of PV systems for different Canadian locations. These models, of course, require reliable data on the solar insolation levels and weather patterns at the proposed site of the PV station. However, historical insolation data are not always available. Thus,in order to simulate the performance of PV systems, predictive methods [20,23] are also required for estimating hourly insolation data for those sites where historical measurements are not available. It is our recommendation that EMR continue to fund the collection of insolation data and that the funds should be made available to develop computer programs to: (1) simulate the operation of PV systems under various conditions and (2) help in the design and optimization of PV systems.

5.2 BOS POWER-RELATED COSTS

Although, BOS power-related costs, e.g. power conditioning units, AC and DC subsystems, and switchyard costs, should also be optimized, they are not as important in determining the competitiveness of PV utility stations as are the BOS area-related costs. This is shown by analysis of EPRI's levelized electricity cost (LEC) equation that is often used to determine the cost of PV generated electricity (see Appendix A). The sensitivity of the LEC to BOS

power-related costs is small compared to the sensitivity of the LEC to either BOS area-related or module costs.

An important component in PV utility generation is the DC to AC inverters, i.e., the power conditioning unit. Inverters are already available in many sizes and no technological breakthroughs are required to manufacture large (5 MW) units. The cost of large, efficient inverters is presently quite high because these units must now be custom designed. Costs are expected to decrease as the number of units manufactured increases.

It is interesting to note that Canada has extensive experience in the use of large DC to AC inverters. The longest high-voltage DC power lines in the world are located in Manitoba and Canadian companies are international leaders in the design of these high-voltage lines [104,105]. (DC power lines are more efficient than AC power lines over long distances.) Thus, Canada already possesses extensive experience in the use of large scale DC to AC power conversion. However, it seems that the inverters are designed and built by foreign companies, e.g., ASEA of Sweden [105].

5.3 BATTERIES

Battery storage is an important component of PV stand-alone systems. Batteries are expensive. Lead-calcium batteries, which are often used with PV systems, cost about $150/kWh [26,106]. A seven day battery storage system for a one Watt system, for example, would cost $25. Therefore, it is not surprising that the battery packs for many PV systems cost more than the PV modules themselves. Consequently, it is necessary to design systems so that battery costs are minimized.

The cost of the battery system will depend of the type of battery chosen. Although many batteries are available, lead acid batteries are the most popular because of their relatively low cost. Various types of lead acid batteries are available on the market, e.g., golf cart batteries, and some manufacturers have even designed batteries specifically for use with PV systems [107].

Once a battery has been chosen, it is important to size the battery pack correctly in order to reduce costs. For this purpose, it is essential to know the operating characteristics of the batteries under the expected operating conditions. In Canada, many small PV systems are used under severe temperature conditions, i.e., low temperatures. Often, data on battery performance under these conditions is not available. This leads to oversizing of the battery pack, an expensive practice, in order to: (1) improve the reliability of the system, which is essential for remote applications and (2) protect the batteries from deep discharges.

In an ideal world, it would be the job of the battery manufacturers to provide the data on battery characteristics and performance under severe conditions. However, since many batteries used in PV systems are not made specifically for PV applications, the performance data are not being provided by the manufacturers. EMR should continue to provide funds to determine the performance characteristics of batteries under severe conditions in order to promote the use of PV systems in Canada's north. Furthermore, development of simulation programs that can be used to optimize PV-battery systems, including PV/diesel/battery systems, should be strongly encouraged.

We recommend that PV R&D funds not be used to support development of new PV batteries. Battery costs will only be lowered if they are mass produced. If the market for PV batteries increases significantly, then, no doubt, the battery manufacturers themselves will spend the research dollars needed to improve the performance of PV-battery systems.

It has often been suggested that the availability of cheap battery storage systems will make PV utility stations much more viable. However, this is not necessarily the case [18,106], unless PV stations produce cheaper electricity than base-load power stations. The availability of cheap battery storage, for example, would allow utilities to charge the batteries with low-cost (base-load) off-peak power and to discharge the batteries during peak periods. It is interesting to note that EPRI and Southern California Edison are planning to build a $14M 10MW/40MWh battery storage plant [106]. The purpose of this plant is to demonstrate the economic advantages of using battery storage to: perform load-levelling, provide spinning reserves, and provide frequency and voltage control. Lead-acid batteries will be used because the advanced batteries [108] are not fully developed with proven reliability. The batteries themselves represent ~55% of the cost of the facility.

5.4 PV-HYBRID SYSTEMS

Village power systems could provide an important market [25,26] for PV modules until the PV utility market becomes available. PV power for remote (off-grid) villages will be the most viable application in the near-term. These stand-alone systems will not be simple PV-battery systems, especially in areas with low average insolation levels, because of the high cost of battery storage. Thus, once the cost of PV power becomes competitive with other electricity generating systems, it is expected that PV-diesel hybrid systems (including PV/diesel/battery systems) will be used to provide village power.

In the village power market, PV-diesel systems must compete with simple diesel systems (and other electric generating systems). Because of the high cost of PV modules, it is doubtful that existing diesel generating stations will be converted to PV-diesel systems, unless fuel prices increase dramatically. Thus, the best markets for PV-hybrid systems are remote villages that (i) do not now possess electrical power and (ii) require additional

generating capacity or must replace existing diesel generators.

The savings in fuel costs associated with use of PV-hybrid systems, rather than diesel generators, must compensate for the higher capital cost of the PV system. Thus it is essential to optimize the design and operation of the PV-hybrid system in order to maximize fuel savings. However, experience with PV-hybrid systems is limited and so the cost of these systems cannot be accurately determined. To this end, EMR should support PV-diesel hybrid demonstrations in order to accumulate design and operating experience and to provide better economic data.

The development of Canadian expertise in PV-hybrid systems will be of economic benefit to Canada. The Canadian market for PV-hybrid village systems is not insignificant in terms of the current market for PV solar cells. More than 100 MWp of PV modules would be required to replace part of the electricity, 0.70 TWh [109], which is currently generated by diesels in Canada. However, the potential savings in fuel-oil alone (maximum of ~10 PJ, or 0.3% of Canadian oil demand) are not enough to support a large R&D effort in PV-hybrid systems. The R&D effort can, however, be easily justified in terms of the potential for cost savings, job creation, economic and regional development and, exports to Third World countries. We envisage that Canada will be able to compete in this market through the design, sale and installation of complete PV-hybrid systems rather than through the sale of PV modules. Development of PV-hybrid systems in Canada will provide Canada with the design tools, experienced personnel and reputation required for it to compete in this industry, especially in Third World Countries where many villages are not nov connected to the electrical grid system. Thus, the development of PV-hybrid systems should be strongly encouraged.

Finally, we should point out that PV-hybrid systems for village power must also be competitive with the cost of extending the electrical grid. In fact, more than 25% of the remote communities in Canada that would be suitable for PV-hybrid systems will be connected to the grid by the year 2000 [26]. Consider, for example, the recently completed power line to Churchill, Manitoba. This 270 km line, built at a cost of $27 million dollars, replaces diesel generators with a total capacity of 11.3 MW (~45% of the diesel generating capacity in Manitoba [104]). Thus, PV power generation, at today's price, is not competitive with grid extension to semi-remote villages with large power requirements.

6. ECONOMIC ANALYSIS FOR PV UTILITY POWER

Utility PV systems are more economical that rooftop systems [18,33] because of the costs associated with marketing, distribution and grid connection. It is estimated that rooftop PV systems would cost three times the factory price whereas a utility could buy modules in bulk at only 1.5 times the factory cost [18]. Consequently, the cost of PV utility power will determine

the long-term economic viability of PV systems.

The cost of PV generated electricity is an important factor in determining the ultimate acceptance of PV utility power. However, it is not the only criterion that will be used. PV power cannot, for example, generate power on demand. Therefore, it will not be used to provide base-load power. The variability in PV power output will be a strong deterrent to the acceptance of PV power, since the utilities have no experience with such power sources. On the other hand, PV power stations are nonpolluting and can be built in rapidly installed modular units. This will give PV stations an advantage if, for example, stringent environmental controls are put on coal plants or if, as in many states in the U.S.A., utilities are not allowed to include charges for construction-work-in-progress in their rate base.

The Electric Power Research Institute has derived an equation [18,110] which can be used to estimate the cost of PV utility generated electricity. As a baseline for determining PV module cost and performance targets, an allowable current-dollar levelized electricity cost (LEC) of $0.15/kWh has been selected. This cost is midway between the projected energy costs from new oil and coal generation plants and is comparable to the electricity cost from new coal stations which operate at capacity factors expected for PV utility stations, i.e., 20 to 30% [18]. It should be emphasized that energy storage systems are not included in EPRI's analysis, i.e., the PV power is supplied directly to the grid.

The U.S. Department of Energy has used the EPRI analysis to set its long-term (late 1990's) technical targets [14,110]. In order to achieve the LEC goal of $0.15/kWh the required technical goals for flat-plate modules are as follows: (1) module efficiencies (AM1.5, 28°C) of 13 - 17%, (2) module costs of $40 - 75/m^2, (3) BOS area-related costs of $50/m^2, (4) BOS power-related costs of $150/kW and (5) system-life expectancy of 30 years. The dollar figures are in 1982 U.S. dollars. More importantly, if these technical targets are met, the established goal, i.e., LEC of $0.15/kWh, will only be achieved for PV power plants located in the Southwest U.S. where insolation levels are high.

We have applied EPRI's equation to estimate the cost of PV generated electricity for Canadian locations. Before going into details, a few general remarks concerning the EPRI equation are warranted. First, sensitivity analysis can be used to determine the least important parameters in the equation (see Appendix A). This shows that the LEC is not very sensitive to changes in the BOS power costs or the O&M costs. Of course, these costs should still be minimized in order to make PV power more competitive with present-day electricity generation plants.

Second, the LEC is approximately equally sensitive (see Appendix A) to the following parameters: capacity factor, insolation level, module efficiency,

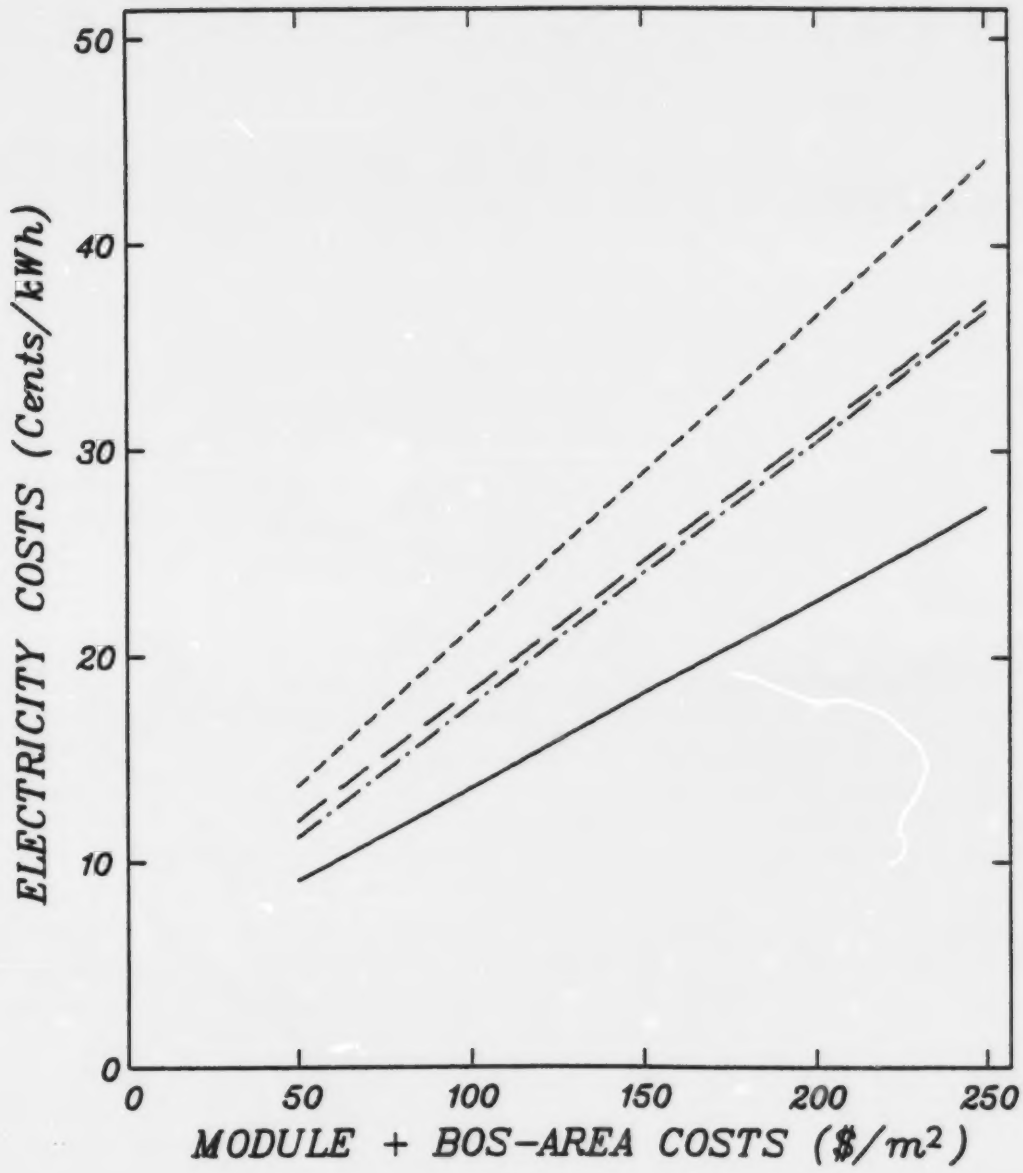


FIGURE 9 Levelized electricity costs versus module plus BOS-area costs for: (———) a site in U.S. Southwest; (- - - -) a Canadian site; (_._._.) a Canadian site, k = 8.5%, i = 4.5%; and (__ __ __) a Canadian site, 15 year write-off period for the fixed charge rate (see Appendix A). The discount, k, and inflation, i, rates are 12.5% and 8.5%, unless otherwise specified.

total of the module plus BOS-area costs, and the fixed charge rate (or levelized carrying charge), which essentially represents the depreciation expense of the power plant. This means, for example, that LEC will increase by about a factor of 2 if either the insolation level decreases by a factor of 2 or the module plus BOS-area costs increase by a factor of 2.

In applying EPRI's equation we have made the following assumptions, unless otherwise specified: (1) the module efficiency is 15%, (2) the BOS-power costs are \$250/kW [26], (3) O&M costs are \$2.28/m^2 per year, (4) the plant lifetime is 30 years, (5) the "write-off" period for calculation of the levelized carrying charge is 10 years (see Appendix A), and (6) the discount and inflation rates are 12.5% and 8.5%, respectively. These parameter values define our reference PV plant. The parameter values are sometimes varied in order to determine the effect of these parameters on the LEC.

In Figure 9, the LEC for various cases is shown as a function of module plus BOS-area costs. The solid curve is the LEC for a site in the Southwest U.S. whereas the top dashed curve is representative of a site in Canada. If the module plus BOS-area cost is \$125/m^2 then the LEC is \$0.16/kWh in the Southwest U.S. but \$0.25/kWh at a Canadian location. Thus, the location of the PV power plant will have a pronounced effect on the economic viability of PV stations. The figure also shows that the calculated levelized electricity costs are affected by the economic assumptions and the accounting principles used to write-off the plant.

It should be pointed out that today's module plus BOS-area cost is more than \$800/m^2. Therefore, significant cost reductions in both the module costs and the BOS-area costs are required before PV power stations will be able to provide power at less than \$0.30/kWh. This will require the introduction of new technology for the production of flat-plate modules, i.e. either the introduction of low-cost and efficient thin-film solar cells or the production of high-efficiency ribbon crystalline silicon solar cells. The technical and cost targets are very stringent, especially for Canadian locations. There is more confidence in the PV community of achieving the technical goals, i.e., module efficiency and 30 year lifetime, than the cost targets [45].

In Figure 10 we show the LEC as a function of module efficiency for fixed module plus BOS-area costs and for different insolation levels. This figure shows that the LEC is inversely proportional to the module efficiency. That is, increasing the module efficiency from 20 to 25% has a relatively smaller effect on the LEC than increasing the module efficiency from 10 to 15%. Thus, once a certain "critical" module efficiency has been attained, it becomes more advantageous to reduce BOS-area or module costs than to increase the efficiency of the module. Again, the influence of the site of the PV station, i.e. the insolation level, is apparent in this figure.

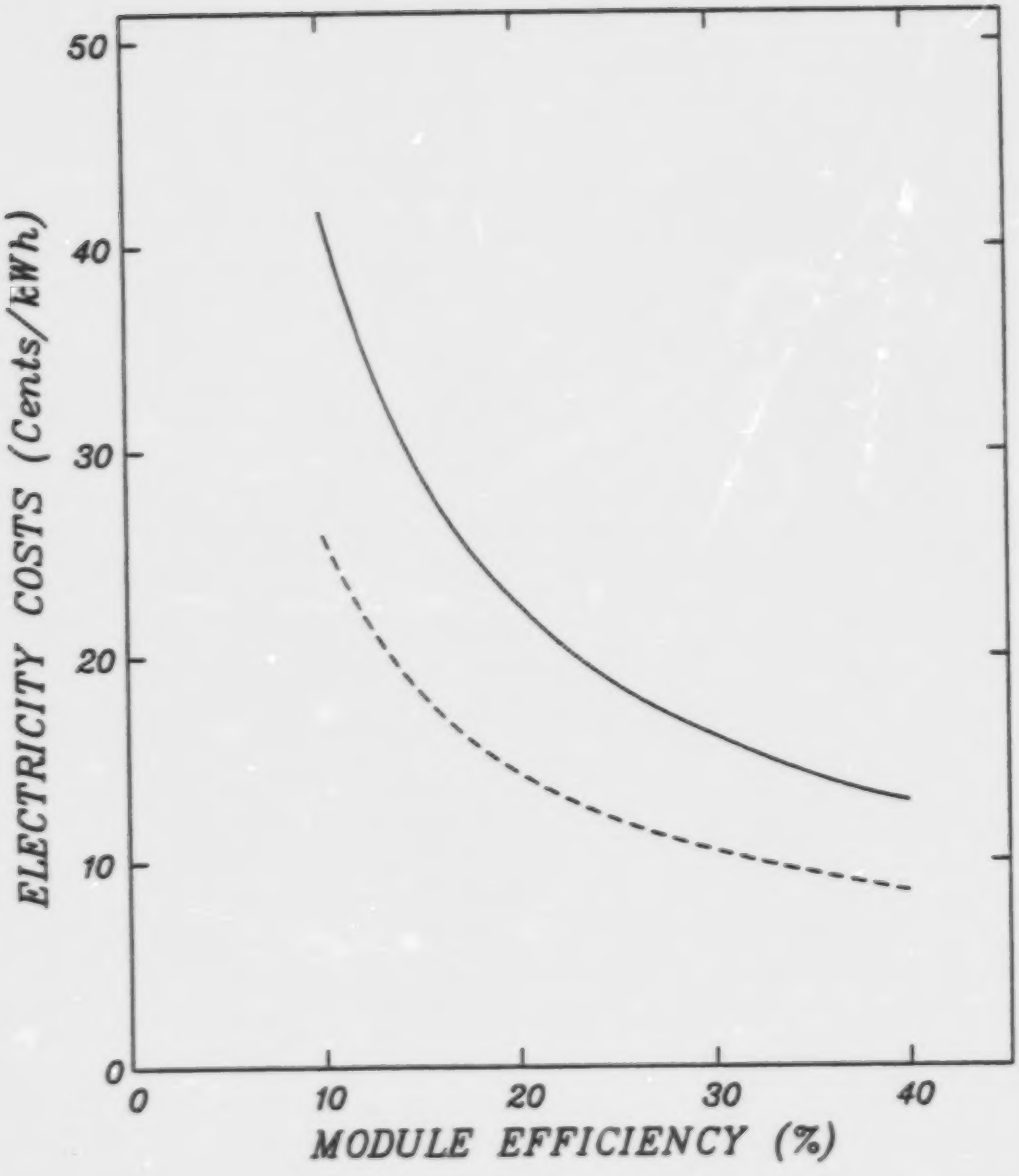


FIGURE 10 Levelized electricity costs versus module efficiency for: (———) a Canadian site, and (- - - -) a site in U.S. Southwest. The module plus BOS-area cost is $150 per square metre.

We have applied EPRI's equation to calculate the LEC from conventional power stations (see Appendix A). This comparison is somewhat artificial since hydro stations, for example, may have longer lifetimes than PV stations and can produce power on-demand. Moreover, the LEC depends strongly on the economic assumptions that are made in the calculation. (We assume that the inflation and discount rates are 8.5 and 12.5%, respectively, and that the write-off period for the fixed charge rate is 10 years.) Nevertheless, this rough comparison should provide valuable information.

Consider a hydro station with O&M costs of \$3.75/MWh [111] and a capacity factor of 0.75. The LEC is given by the equation

$$\text{LEC (\$/kWh)} = 0.009 + 0.028 \times \text{CAP}$$

where CAP is the capital cost of the hydro station in \$/W. Thus, the LEC is \$0.093/kWh for a station costing \$3000/kW. If the capacity factor is only 0.50, then the LEC is given by the equation

$$\text{LEC (\$/kWh)} = 0.009 + 0.041 \times \text{CAP}$$

The Limestone Generating Station, which is now being built in Manitoba, costs ~\$1.43 billion dollars and has a generating capacity of ~1280 MW [104]. On this basis, if the capacity factor is only 0.50, the LEC from this station would only be \$0.040 or \$0.055/kWh, depending on whether or not indirect costs have been included in the \$1.43 billion dollar figure. Therefore, PV power will not be competitive with hydro power for the foreseeable future.

A similar analysis can be carried out for nuclear power stations. For O&M costs of \$7.5/MWh [111] and a capacity factor of 0.70, the LEC for the nuclear station is given by

$$\text{LEC (\$/kWh)} = 0.017 + 0.030 \times \text{CAP}$$

where CAP is the capital cost of the plant in \$/W. The cost of the Darlington Nuclear Station in Ontario, for example, is ~\$2300/kW [112]. Thus, we estimate that this nuclear station would produce power for a LEC of ~6.3 or 8.6 cents/kWh, depending on whether or not the indirect costs have been included in the quoted cost of the station. In comparison, we see, from Figure 9, that the reference PV station, in Canada, can generate power for less than 15 cents/kWh only if the module plus BOS-area costs are less than \$60/m^2.

Finally, we carry out a LEC analysis for a coal station with a capacity factor of 0.70. If the O&M costs are \$22.5/MWh [111], then the LEC for the coal station is given by

$$LEC\ (\$/kWh) = 0.052 + 0.030 \times CAP$$

We could not find recent information on the construction costs for a coal generating station in Canada. However, in Utah, a coal station was recently built for a capital cost of ~$1100/W [113]. Using this figure we calculate that this coal station would produce power for a LEC of 8.5 cents/kWh.

In view of the above analysis, we do not expect PV utility power, to be competitive with conventional energy sources in Canada for at least another 25 to 30 years. In order for PV power stations to compete with hydro, coal or nuclear power stations in Canada, the total module plus BOS-area costs must be less than ~$75/m^2. This will be a difficult target to achieve. However, PV power stations could still be built in Canada by the turn of the century if: (1) the future price of coal increases sharply and/or stringent pollution controls are imposed on these stations, (2) all hydro power sites have been exploited, and (3) opposition to nuclear power makes it an unacceptable option for Canadians.

7. GLOBAL STATUS OF PHOTOVOLTAIC R&D

7.1 UNITED STATES

As has been previously mentioned, the energy crisis of the seventies gave PV R&D a major push. Thus, the major aim of the global PV R&D effort was and still is to develop a renewable energy source. This is particularly true in the U.S.A. where the objective of the DOE's National Photovoltaic Program is the development of competitive PV utility power. To some extent, this explains why U.S. PV companies do not dominate the consumer market for PV cells. The U.S. companies, taking their cue from the DOE, focused their sights and R&D effort on the potentially large but long-term utility market. The Japanese companies, on the other hand, saw that the replacement of expensive battery power in consumer goods such as calculators and watches provided a golden opportunity for the exploitation of low efficiency, thin-film, solar cells.

The U.S. government has spent more than $4000 M on programs to develop solar technology [110]. More than $750 M has been allocated, in the last decade, specifically for PV research and development [14]. The goal of DOE's PV program is to establish a competitive energy alternative [110]. In order to attain its stated objective - PV utility power - the U.S. National Photovoltaics Program sponsors "long-range, high-risk, PV research and development - R&D industry is unlikely to take on due to the costs and risks involved" [110]. Private industry is expected to spend its own money for near-term PV technology development and product commercialization.

Although the PV budget reached $150 M in 1980, it is nov only ~$43 M [12]. The Flat-Plate Solar Array Project, which vas administered through the Jet Propulsion Laboratory (JPL), has been terminated [28,14] because of the budget cutbacks. The objective of this program vas to develop industrial techniques to lover the cost of flat-plate PV modules that use silicon as the active PV material. Consequently, much of the vork on silicon ribbon materials, silicon purification, and module design and production has been curtailed. Similarly, the concentrator collector program, administered by Sandia National Laboratory, has also been terminated.

Today's DOE PV R&D budget is, in part, administered by SERI ($26 M). Only half of SERI's PV budget is used for in-house research, vhich is carried out by a staff of 80 people [13]. The remaining funds are used to support joint or independent PV R&D projects in universities or industry. For example, SERI has recently [115] signed a three year, $8 M cost-sharing contract vith Energy Conversion Devices (Troy, Michigan) for development of high-efficiency, amorphous-silicon alloy, (tandem) solar cells.

SERI's mission is to carry out the basic, long-term, high-risk research, that is needed to attain DOE's technical targets (see Section 6) for module efficiency and costs. SERI is nov emphasizing the following materials research projects: (1) amorphous silicon materials (for single-junction and tandem solar cells), (2) polycrystalline thin-film materials, e.g., $CuInSe_2$, and (3) III-V materials for high-efficiency concentrator solar cells, e.g., $GaInP_2$/GaAs tandem cells.

The research priorities at SERI are set according to the currently perceived ability of the various technologies to attain DOE's technical targets. Moreover, specific targets, in terms of solar cell efficiencies, are set for each project. For example, in 1983 the efficiency goals of the three-year DOE-industry program vere: (1) 12% efficiency for small-area cells (1 cm^2), and (2) 8% efficiency for large-area cells (1000 cm^2).

Private industry in the U.S. also supports PV R&D. ARCO Solar is the world's largest supplier of PV modules. Most of its modules are based on single-crystalline silicon technology; but recently it has started to manufacture a-Si modules. More importantly, ARCO Solar is nov concentrating its R&D effort in the development of high-efficiency, thin-film solar modules.

The ARCO Solar research centre, vith a staff of 100 and a budget of ~$14 M, is nov working vigorously to develop large-area deposition methods for $CuInSe_2$ thin-films [35]. The first goal is to manufacture inexpensive, efficient (8-11%), large area CdS/$CuInSe_2$ devices. Eventually, they expect to develop highly-efficient, multi-junction solar modules based on a-Si and $CuInSe_2$ technologies [10,11]. Small laboratory (tandem) cells nov have efficiencies of up to 13% and J.H. Caldvell, president of ARCO Solar, believes that ARCO Solar will achieve commercial-device efficiencies in the 18% range

within five years [12].

ECD is another U.S. company actively involved both in PV research and the manufacture of a-Si solar cells [8,68]. ECD has developed fluorinated a-Si tandem cells. Very thin a-Si:F layers are used in these devices to reduce the degradation of conversion efficiency caused by exposure to sunlight. ECD has produced a-Si tandem solar cells with efficiencies of up to 13% [117]. These cells have excellent stability. A cell with an initial efficiency of 11.2% retains 90% of its conversion efficiency after 2500 hours of continuous exposure to AM1 light. It should be noted that the Japanese have made a-Si tandem cells with similar stabilities without using fluorine [117].

Finally, we also mention the PV R&D work which has been supported by the Electric Power and Research Institute (EPRI). EPRI is a utility supported agency, therefore, it sponsors PV research that would be of interest to utilities, e.g., economic analysis of PV costs [18], status review of PV technology [45], and studies on the effect of PV power on the operation and management of utility systems [18].

EPRI also supports long-term basic research; especially, in areas that are important for the development of PV utility power, but which is not being carried out either by the DOE or by the photovoltaics industry. A perfect example is the work carried out at Stanford University which led to the development of the point-contact silicon solar cell for concentrator applications [38,39]. This cell has achieved 28.2% efficiency in the laboratory and is approaching pilot-scale manufacture under an EPRI contract [39]. The importance of long-term support was emphasized by R. Swanson (Stanford, the research leader on the project) [39]. "One of the most important factors in our success was the long, stable funding base that EPRI provided. It allowed us to build a team of people with special expertise."

It is impossible for us to review all the work being carried out in the United States. This task has already been carried out by SERI [21]. However, we conclude with a few comments: (1) important advances in PV technology are only likely with a long-term but focused R&D program, (2) the development of inexpensive, high-efficiency thin-film solar cells has a high priority in PV research, and (3) R&D in crystalline silicon solar cells has been curtailed because of the perception that dramatic cost reductions are not possible with this technology (compared with thin-film technologies).

7.2 JAPAN

The Japanese government and, more importantly, the Japanese consumer electronics companies are actively involved in photovoltaic R&D. The government allocates about $40 M annually [118] to support photovoltaic R&D in industry and universities. The government funding is provided through the Sunshine Project, administered by the Ministry of International Trade and Industry, and the New Energy Development Organization. The Japanese PV R&D effort is mainly directed toward the study of a-Si PV devices [6,9].

Japanese scientists and engineers began a major R&D effort to study a-Si thin films in 1977, after the announcement of the photovoltaic effect in amorphous silicon by RCA Laboratories. In 1980, less than three years later, Sanyo Electric introduced the first indoor-light powered calculators and watches on the world market. Fuji Electric and Sharp Electronics quickly followed suit. These consumer products use low-efficiency amorphous silicon solar cells in order to extend battery lifetimes. In 1985, Japan became the world's leading producer of PV cells [12]. Today, Sanyo Electric alone has an annual production capacity of 5 MWp [11].

The Japanese PV industry has been very successful in exploiting the consumer products market but not the power systems market. Single-crystal silicon PV modules still dominate the latter market because of their reliability, stability, high conversion efficiency and long lifetime. Amorphous silicon solar cells will begin to replace crystalline silicon solar cells in the power systems market only if their efficiency, lifetime and stability are increased and the cost of production is decreased. This can be achieved by development of efficient a-Si tandem cells and automated production methods.

The most active R&D laboratories for a-Si:H based PV devices are Sanyo Electric, Fuji Electric, Sharp Corporation, Mitsubishi Electric and Osaka University, to name just a few. Their major research goals are to improve the efficiency and stability of a-Si solar cells and to reduce production costs. This involves the investigation of new materials, e.g., a-SiC:H [55], and new device structures, e.g., tandem cells. At Osaka University, for example, efficiencies of 9.4% and 12.3% have been reported for a-SiC:H/a-Si:H solar cells [119] and a-Si:H/poly-Si solar cells [120], respectively. New film fabrication methods, e.g., photochemical vapour deposition [6,121,122], are being studied in order to improve the quality of the a-Si films and hence the performance of a-Si solar cells.

Sanyo Electric, Japan's largest manufacturer of a-Si solar cells, has made great strides in improving the quality of a-Si films. Basic research carried out to study the effect of film fabrication parameters on the properties of the a-Si films [123] has shown that impurities reduce the conversion efficiency [59,124] and decrease the stability [125] of a-Si solar cells. Based on this information, Sanyo Electric developed a consecutive,

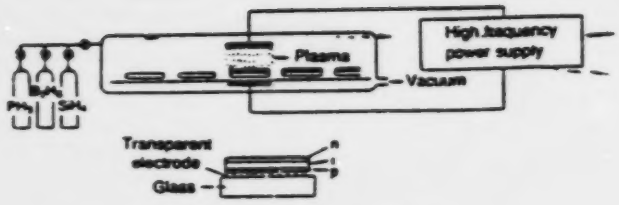
separated reaction chamber system (see Figure 11b) in which each layer of the solar cell is fabricated in a different chamber. This avoids contamination of the various layers by residual dopant gases. More recently [59], Sanyo Electric has improved this fabrication technology by developing a so-called "super separated ultra-high vacuum (UHV) reaction chamber system" (see Figure 11c). With this technology, Sanyo Electric has manufactured a-SiC:H/a-Si:H solar cells with efficiencies of 11.7% for 1 cm^2 cells and 9.7% for 100 cm^2 cells [59].

Tandem cells require the use of narrow band gap materials such as a-SiGe:H alloys [8,126]. However, these alloys have poor properties, therefore efforts are being made in Japan [127] and elsewhere [68,128] to improve these alloys by incorporating fluorine in the a-Si films. Tandem structures can also be used to reduce light-induced degradation of a-Si solar cells. The light-induced degradation of the cells decreases with decreasing i-layer thickness [67,72]. Hence, tandem structures with thin i-layers can be used to increase stability without decreasing efficiency [68]. Kuwano et al [125] have reported that the stability of the tandem structure solar cells is very good and their performance remains stable after exposure to light for several hundreds of hours.

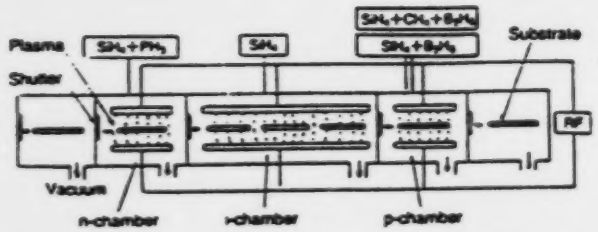
Japanese R&D has also led to improvements in the mass-production of a-Si:H based PV devices. Automated production lines are needed to reduce the cost of large area a-Si modules for terrestrial applications. Nakano et al [59], for example, have developed a new laser patterning method for the production of integrated solar cell modules. Typical structures of integrated a-Si solar cell modules are shown in Figure 6. The Type II structure is better suited for the fabrication of large area solar cell modules because this structure reduces the power loss due to series resistance.

As has already been mentioned, Japan's PV R&D effort is concentrated on the study of a-Si based thin films and much less on the study of non-Si thin films. This may be due to the fact that a-Si alloys offer many technological and economic advantages over non-Si thin films for spinoff applications in microelectronics [7,128] and a-Si image sensors [129]. This is particularly important for the consumer electronic companies which are constantly looking for commercial opportunities. However, some Japanese companies are interested in non-Si thin films. We now describe some of their work on CdTe thin films [130].

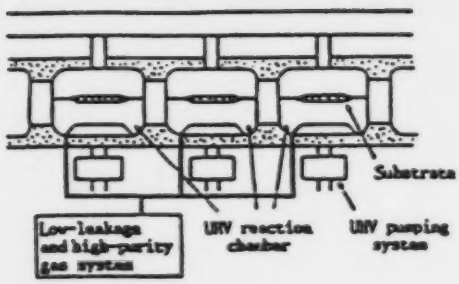
CdTe/CdS cells can be manufactured using screen printing and sintering techniques [130]. Matsumoto et al [77], for example, have achieved a conversion efficiency of 12.8% for a small area (0.78 cm^2) screen-printed CdTe/CdS solar cell. The major difficulty in this technology is to obtain a good ohmic contact between the semiconductor and the metal electrode [10]. The high resistance impairs the performance of the PV cell. Matsushita Co. has perhaps solved this problem. The company has reported [10] making 5%-efficieny 0.5 m^2 CdTe modules



(a) Single Reaction Chamber Method



(b) Consecutive, Separated Reaction Chamber Method Developed by Sanyo



(c) Super UHV Separated Reaction Chamber System

FIGURE 11 a-Si:H solar cell fabrication methods. After Nakano et al [59].

and 12.8%-efficiency 1 cm^2 cells (using the screen printing technology), and has demonstrated the reliability of these modules in outdoor stability testing [10]. More importantly, Matsushita has signed a contract with Texas Instruments to supply CdTe cells for calculators at a rate of 1 million units per month. This will be the first commercial application of CdTe solar cells [10] and makes CdTe solar cells a competitor of a-Si based cells.

Finally, let us describe some of the work at the Hoxan Corporation. Hoxan has the world's largest fully automated PV factory for the production of crystalline silicon PV modules. Moreover, Hoxan is actively involved in the development of silicon sheet material. Hoxan has recently developed a new spinning process to mass-produce silicon sheets [131,132]. Impurity contamination has been reduced as low as 0.3 ppm (close to that of CZ silicon crystals) and conversion efficiencies higher than 10% have been obtained for 100 cm^2 solar cells [133]. Further research is needed to reduce the thickness of the silicon sheets. The production of thin (less than 0.1 mm) silicon sheets at a high growth rate will result in a significant cost reduction and may lead to large scale applications of PV modules. This research direction will compete with the a-Si films in the next decade, especially if the stability problems associated with a-Si cells are not solved.

7.3 WORLD MARKETS

The major trends in photovoltaic world markets, for the last decade, are shown in Figure 12. World production increased exponentially during the 1976-83 period, while the rate of growth has moderated substantially during the 1983-86 period. Amorphous silicon module production, largely from Japan, increased substantially from about 1 MWp in 1982 to about 11 MWp (36% of total) in 1986. In 1986, the total world production was about 30 MWp, an increase of about 3 MW from 1985 levels. Japan, the U.S.A. and Europe accounted for 95% of the total world production. By comparison, the total Canadian production was estimated at about 54 kWp in 1984.

The reduced rate of growth of the photovoltaic industry in the last four years is largely attributed to the decline in government purchases, particularly in the U.S.A.. Most of these purchases were intended to encourage the industry to develop and were related more or less to programs aimed to demonstrate the viability of photovoltaics in electrical power generation. The latter factor becomes more evident by looking at the declining U.S.A. production levels and the more or less constant world levels, once the a-Si contribution (which has so far been serving the consumer market) is subtracted from total world production. It is evident that the energy motivation in photovoltaics is diminishing due to the energy glut mentality of the eighties.

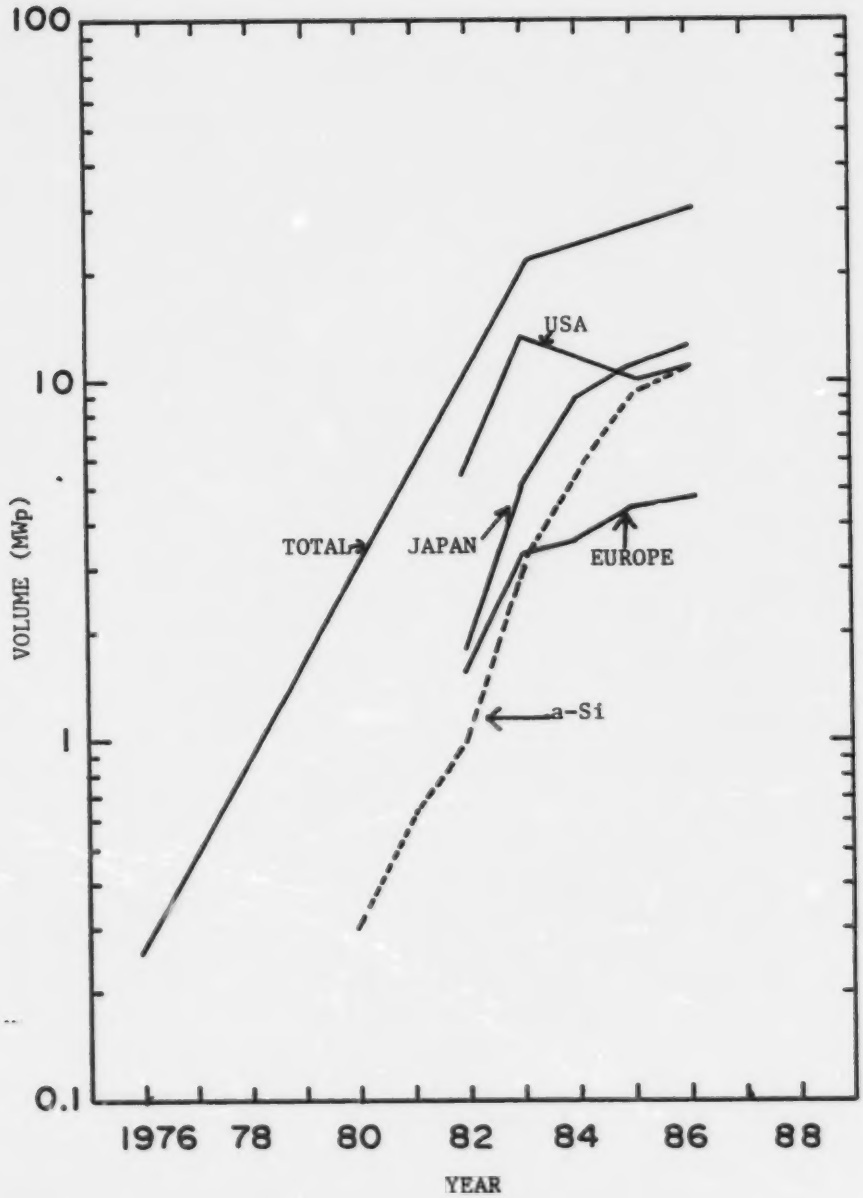


FIGURE 12: Major Trends in Photovoltaic World Markets

Future photovoltaic expansion may have also been put on hold, pending promising developments in the new thin-film technologies. Even a-Si levels appear to show signs of saturation, although it is too early to tell with certainty. This could be explained in terms of saturation of consumer product markets.

Our best forecast is that worldwide photovoltaic markets will continue to grow at about the same rate as for the 1983-86 period, until further significant cost reductions and module efficiency and lifetime stability increases are achieved. The latter are likely to be achieved by thin-film technologies within the next decade. Thus, a conservative estimate of world markets would be about 80 MWp by 1995, and about 130 MWp by 2000. These numbers were obtained by linear extrapolation of the logarithmic trend established during the 1983-86 period. Much higher forecasts were given by Frost and Sullivan and by Maycock. The former forecast annual sales of 100 MWp reached by 1990 and the latter 400 MWp to 2000 MWp by 1995. We feel that both of these forecasts, which are based on significant photovoltaic penetration in utility grid applications, are too optimistic. Our examination of the technological challenges (15% efficiencies, less than $1/Wp cost, more than 30-year lifetime) required for significant utility grid applications show that these are not likely to be met before the end of the next decade. However, we have no doubt that, once these limitations are resolved, photovoltaic markets will meet and exceed even the more optimistic of the above forecasts.

The following are some major international agreements, signed in 1986, which are bound to influence substantially world markets in photovoltaics. It is interesting to note that all of these agreements involve thin-film technologies and target third-world markets.

- ARCO Solar and Interatom GmbH (Siemens Group) of West Germany have signed on agreement (May 1986) establishing guidelines for cooperation in photovoltaics. The key objectives of this agreement are to establish a thin-film manufacturing facility in Europe based on ARCO Solar's technology, to cooperate in a common R&D program and to market products through existing ARCO Solar and Interatom networks.

- ARCO Solar and Showa Shell Sekiyu K.K., a major Japanese oil company, have signed (March 1986) technology licensing and joint venture agreements for manufacturing and marketing of thin-film photovoltaic products developed by ARCO Solar. A joint-venture company, Showa Arco Solar K.K, will be established in Tokyo for supplying the Japanese market, as well as another company, Showa ARCO Solar Far East Pte. Ltd., in Singapore, for supplying the Far East and Pacific area markets.

- Energy Conversion Devices and Sovonics Solar Technology of India have signed an agreement (April 1986) to establish a joint-venture company, Surgonics Ltd., for producing photovoltaic systems in India. Surgonics plans to build a plant to produce 5 MWp photovoltaic modules per annum,

initially, and eventually up to 25 MWp for the Indian market. The Indian government has established a plan to provide electricity to about 300,000 villages across the country. The high cost of connecting such villages to a central power grid is the strongest incentive for using photovoltaics for village power in India.

8. CANADIAN PERSPECTIVE ON PHOTOVOLTAICS

The Canadian photovoltaic program, like in other countries, had its origins in the energy crisis of the mid-seventies [23]. Photovoltaics, as well as other renewable energy alternatives, were justified then on the basis of their potential to displace expensive, non-renewable fuels (oil and gas) in the near-term and to become a significant component of our energy mix in the long-term. In 1973, following the Arab oil embargo and predictions by the EMR "Standard Forecast" that energy demand will double in the period 1974-1984 and then double again before the end of the century, Cabinet instructed EMR to convene an interdepartmental Task Force on Energy Research and Development to review existing energy R&D and formulate recommendations for a new program to address Canada's forecast needs.

The Task Force on Energy R&D published in 1975 its report "Science and Technology for Canada's Energy Needs", which set the goal for the Canadian energy R&D program: To develop the scientific and technical capabilities to achieve self-reliance in energy with minimal environmental, social or economic costs and maximum industrial or quality of life advantages. A number of energy programs were identified and grouped under six major tasks, namely: Conservation, Oil Sands - Heavy Oil - Coal, Nuclear Energy, Renewable Energy, New Liquid Fuels, and Conventional Energy Systems. The Task Force also established, in 1973, the Panel on Energy Research and Development (PERD) with the mission to review and assess energy R&D, coordinate it with government policy, and allocate available R&D funds. During the period FY 75/76 - FY 84/85, PERD allocated a total of $674 M (Can.) in energy R&D. Photovoltaic R&D was funded under the task of Renewable Energy which was administered by the National Research Council of Canada.

The energy glut of the eighties, caused by worldwide economic downturn and energy conservation efforts, resulted in significant curtailment of all energy R&D programs in Canada and worldwide. Major energy R&D funding reductions were announced in Canada during the 1984/85 period, which included the Renewable Energy Program. However, recent developments under the National Conservation and Alternative Energy Initiatives program, announced in 1985 by the Minister of Energy, appear to inject some optimism that Conservation and Alternative Energy may receive in the future increased support through federal-provincial initiatives. Agreements along these lines have already been signed with most provinces and statements by the Minister of Energy, in 1986, reaffirm the Federal Government's position that, despite the decline in world oil

prices, conservation and alternative energy continue to make sense by offering attractive possibilities for reducing energy costs, creating new jobs and expanding exports.

Presently, photovoltaic R&D continues to be funded in Canada, but at a reduced level compared to the period before 1984. Also recent perceptions of the program do not seem to emphasize the energy mandate, because of the current energy climate and the fact that photovoltaics is forecast to be a far longer term option for Canada than initially expected. Instead, photovoltaic applications in replacing expensive forms of electrical energy (batteries, thermoelectric, and thermomechanical generators for remote applications and consumer products) and photovoltaics for foreign markets, appear to be the dominant justification of the program.

Despite the current energy glut and the current limitations of the technology, we believe that in the long-term the need of energy alternatives will be more paramount than that of the seventies, and present photovoltaic limitations - given enough attention and resources - will be overcome. With respect to the latter, we believe that photovoltaic technology limitations are far less severe as, for example, those associated with generating electricity by fusion, an energy option for which Canada is pursuing R&D. Thus, we believe that, in addition to the current applications of photovoltaics and the prospects of foreign markets, the following should continue to be a sound rationale on why Canada should have an R&D program on photovoltaics:

1. To displace in the future expensive fuels used to generate electricity. This is justified not only in terms of future economics, but also in terms of conservation of a non-renewable resource.

2. To reduce reliance on coal-fired power plants and thus minimize the environmental impact (acid rain, greenhouse effect) of using coal to generate electricity.

3. As a security, in case of failure by the public to accept nuclear fission as a safe and environmentally sound method of generating electricity.

4. As a long-term energy option, much like fusion; and as a safeguard, in case electricity generation by fusion does not prove to be economically or technologically achievable as early into the future as expected.

8.1 CURRENT APPLICATIONS OF PHOTOVOLTAICS IN CANADA

Table 1 lists present (1977-85) and future Canadian applications of photovoltaics, as forecast by the TRU study [26]. The major trends are also

TABLE 1: Photovoltaic Power Systems: Canadian Demand Data kWp/a) by Application and Segment (Ref. 26)

APPLICATION	1977	1980	1982	1983	1985	1990	1995	2000
CURRENT USES	3.2	8.2	21	39	47	46	47	69
COMMUNICATIONS	1.6		5.3	11	10	14	7.0	.5
- radio and repeaters			3.9	11	8.6	12	6.1	.2
- other communications			1.4	.3	1.6	1.6	.9	.3
MONITORING/SENSING EQUIPMENT	0.8	1.2	3.0	5.6	9.4	8.5	7.9	8.3
- water level monitor			.6	.3	1.5	.4	.2	0
- environmental monitor			.8	.5	1.1	.3	.2	0
- seiseic monitor			0	.2	1.1	.1	.1	.1
- remote transmission unit			1.4	4.6	5.1	.7	.4	.1
- traffic counter			0	0	.1	0	0	0
- other m/s devices			.1	0	.6	7.0	7.0	8.0
MARKING AND WARNING DEVICES	0.7	2.0	4.8	14	15	10	9.9	1.8
- navigational lights			4.8	12	12	8.0	8.0	.4
- radio beacons			0	2.3	3.2	1.1	.7	.2
- other warning lights			0	0	.2	1.2	1.2	1.2
RESIDENTIAL USE	0	.2	.9	2.0	3.0	8.6	17	44
- home power			.9	2.0	2.8	7.5	16	40
- roof fan			0	0	.1	.1	.1	.1
- other residential			0	0	.1	1.0	1.0	4.0
LABORATORY TEST	0.1	2.3	3.3	2.1	9.0	3.0	3.0	6.0
- commercial			.3	1.0	8.5	2.5	2.5	
- educational			3.0	1.0	.5	.5	.5	
OTHER CURRENT USES	0	.2	2.4	.5	.5	2.0	2.0	8.0
- retail			.5	.5	.5	1.5	1.5	6.0
- other			1.8	0	0	.5	.5	2.0
NEW USES BEFORE 1990	0	0	0	0	0	50	220	420
CORROSION PROTECTION			0	0	0	35	110	180
- oil and gas related			0	0	0			
- bridges			0	0	0			
- other corrosion protect			0	0	0			
REMOTE LIGHTING			0	0	0	3	35	66
- railway/road related			0	0	0			
- other lights			0	0	0			
WATER PUMPING			0	0	0	10	71	130
OTHER MEDIUM TERM USES			0	0	0	1.5	11	40
NEW USES 1990-2000	0	0	0	1	0	0	0	860
VILLAGE POWER			0	0	0	0	0	500
MEDIUM LOAD CENTRE			0	0	0	0	0	200
RESIDENTIAL GRID CONNECT			0	1	0	0	0	10
(CENTRAL STATION)			0	0	0	0	0	0
OTHER			0	0	0	0	0	150
ADJUSTMENTS	0	0	1.4	2.8	0	0	0	0
CANADA TOTALS	3.2	8.2	21	39	47	96	270	1400

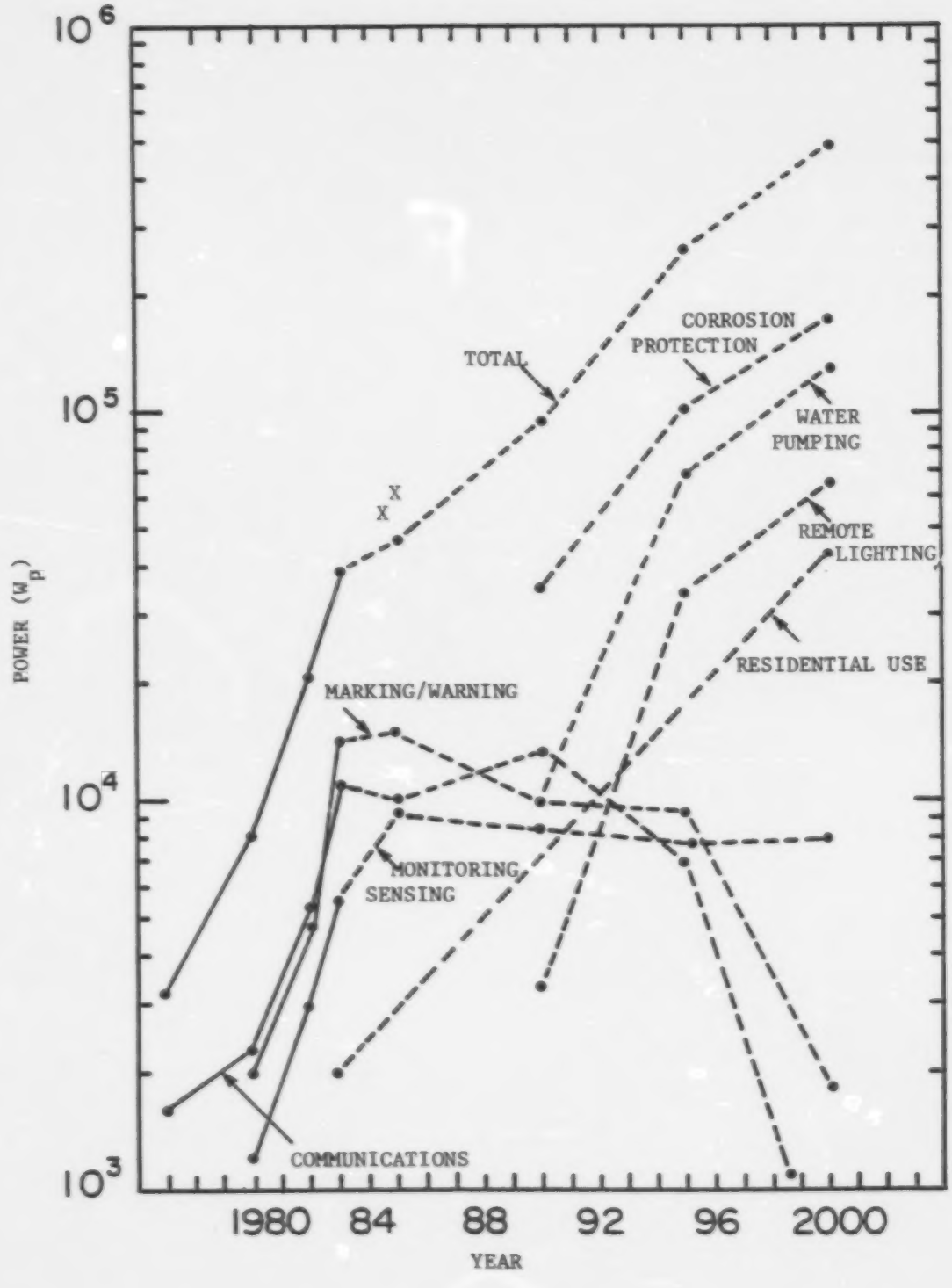


FIGURE 13: Present (——) and Future (---) Applications of Photovoltaics in Canada (Ref. 26); Data indicated by (x) are from Ref. 34.

plotted in Figure 13. The main current applications are in communications (radio repeaters), monitoring & sensing equipment (remote transmission units, environmental and water level monitors), and marking and warning devices (navigational lights and radio beacons). These applications are presently economic and are forecast to saturate over the next decade, as most of existing systems become retrofitted with photovoltaic modules. We consider the forecast for this market as relatively secure over the next decade at about 50 kWp per annum amounting to a value of about $1 M (Can.) per annum for modules and about $3 M (Can.) per annum for complete systems. New applications, expected to become economic with technology developed in the nineties, are in corrosion protection, water pumping, remote lighting and residential use. Forecasts for the latter market are rather speculative and the benefits of going PV are not as obvious. However, assuming that these markets materialize as forecast by the TRU study, as much as 0.5 MWp per annum of modules would be required by the late nineties, amounting to about $5 M (Can.) to $15 M (Can.) per annum in terms of system costs. Finally utility-grid applications of any substantial size are not expected to be economic for Canada in the near-term (prior to the year 2000). The latter applications are discussed separately in this report.

According to data for the 1982-83 period [26,34], the main end users of photovoltaic systems have been the federal and provincial governments, utilities and research and educational institutions. The private sector use of photovoltaic systems amounted to about 20% of total use for the above period. This trend is not expected to change significantly over the next decade.

The Canadian Coast Guard has been the leading government agency in terms of current applications. Other important users have been Environment Canada and Indian and Northern Affairs. Since FY 80/81 the Coast Guard has invested about $3 M (Can.) on photovoltaic systems [134]. These are primarily land-based systems, mainly beacons, but also some radar transponders and fog horns. Presently, the Canadian Coast Guard has installed about 1700 such systems (< 50 Wp each), including ten large ones (0.7 to 10 kWp). They are about half-way in meeting their requirements for land-based systems and are now planning to deploy, over the next few years, photovoltaic systems on about 3500 water-based marine aids (buoys). The Coast Guard is quite pleased with the performance of their photovoltaic systems. They estimate an average payback period of three years and claim substantial savings in terms of the costs for the throw-away batteries used previously.

8.2 PROSPECTS FOR PHOTOVOLTAIC POWER GENERATION IN CANADA

The present (1986) and forecast (2000) electricity generation in Canada are given in Table 2.

TABLE 2: PRESENT AND FORECAST ELECTRICITY GENERATION (TWh) IN CANADA[135]

YEAR	HYDRO	NUCLEAR	COAL	GAS	OIL	OTHER	TOTAL
1986	316.0	68.6	58.7	6.6	5.3	2.4	457.6
2000	383.1	106.1	97.1	9.9	10.3	4.5	610.9

In 1986 457.6 TWh (96.5 GW installed capacity) were generated largely by hydro (69.1%), nuclear (15%) and coal (12.8%). This is forecast to increase, at a rate of about 2.6% per annum, to 611 TWh (118 GW) by the year 2000. The forecast increase is estimated to be made up largely by hydro (44%), coal (25%) and nuclear (24%). For the reasons stated above, it is very unlikely, particularly for Canada, for photovoltaics to become competitive with the above three fuels before the year 2020.

As shown in Figure 9 and discussed in Chapter 6, the U.S. DOE target of generating electricity by photovoltaics at a levelized cost of 15¢/kWh by the late nineties, applies to the U.S. Southwest and equivalent climates [18]. In Canada, due to the lower insolation, the same photovoltaic power plant as for the U.S. Southwest would be generating electricity at about 25¢/kWh. In view of the generally lower electricity costs in Canada, due to abundant hydro and successful deployment of nuclear, the above target is uncompetitive, except for limited applications in remote communities of Northern Canada. Thus, in order for photovoltaics to have the same impact in Canada as for the U.S. Southwest, it must be able to produce electricity at a cost two to three times lower than that targeted by the U.S. DOE program. As shown in Figure 10, this would require technological achievements bordering presently envisaged photovoltaic limitations. Thus, significant generation of photovoltaic electricity is a much longer-term option for Canada.

Electricity generation by oil and gas fuels, which could be targeted for early displacement by photovoltaics, presently amounts to 12 TWh (2.6% of total) and is estimated to grow to about 20 TWh (3.3% of total) by the year 2000. The leading provinces, in terms of oil generated electricity, are Newfoundland (1.8 TWh), New Brunswick (2.3 TWh) and British Columbia (2.0 TWh); in terms of gas generated electricity, Alberta (1.7 TWh) and, to a lesser extent, Saskatchewan (0.3 TWh). Assuming that existing trends in oil and gas use continue beyond the year 2000, when photovoltaics could generate electricity at competitive prices with these fuels, the estimated Canadian market for photovoltaic systems (80% BOS efficiency and a mean insolation of 162 W/m^2) is about 10 to 18 GWp. A minimum size market can be estimated assuming that only internal combustion (diesel) generators can be displaced. Generation of electricity by the latter in 1986 amounted to 0.7 TWh, which

corresponds to about 600 MWp of photovoltaic capacity.

Thus, a likely scenario for photovoltaic deployment in Canada is to first displace diesel generators in remote communities with PV-diesel hybrid systems. This could be realized within the first decade of the 21st century. More efficient/less expensive photovoltaic systems, advances in energy storage devices, and escalating prices of oil and gas fuels, could displace most oil and gas generating capacity within the second decade of the 21st century. This scenario would generate a photovoltaic market of about 1 GWp (~ $1 B) for the first decade and about 10 GWp (~ $10 B) for the second decade.

The timing and extent of further penetration of photovoltaics, i.e., against coal and nuclear, would be too speculative to predict at this stage. The diurnal and seasonal variation of the solar resource, as well as its weather dependence, make it difficult for photovoltaics to compete against base-load fuels such as coal and nuclear; particularly for Canada, where the availability of the solar resource does not match peak electricity demand. It is however possible, because photovoltaic systems have short lead times and capacity can be added in small increments, that the utilities may opt for the planning flexibility of photovoltaics and deploy limited-size power plants (10 to 50 MW) to meet demand without risking future overcapacity. Beyond the latter application, any further photovoltaic penetration would be unlikely to occur within the first quarter of the 21st century and, if it does, it would be based on public concerns about coal and/or nuclear rather than on economic grounds.

In conclusion, photovoltaics are not likely to be a substantial (> 5%) component of the Canadian electricity mix early into the 21st century. However, photovoltaic substitution of oil and gas generated electricity and possibly limited deployment by utilities, for planning flexibility reasons, could generate a photovoltaic market of upto 20 GWp (~ $20 B) during the period 2000 - 2025. Even discounting possible further penetration, we believe that the above market is by itself substantial and warrants Canadian involvement in photovoltaic R&D to ensure that this market is served by Canadian industry for maximum benefit to Canada.

8.3 PHOTOVOLTAIC R&D FUNDING IN CANADA

The National Research Council (NRC) of Canada was the first institution to sponsor photovoltaic R&D in Canada under the Renewable Energy task which was administered by NRC. The NRC funding policy in the early stages (1977-80) of the program was to encourage the development of a Canadian photovoltaic industry and to assess Canadian applications of photovoltaics. By 1980 the NRC program had developed to a balanced national program on photovoltaics, with a total budget of $900 K (Can.) (FY 80/81), and the following main thrusts.

1. Long-term R&D on materials and devices
2. Short-term R&D on cells and encapsulation
3. Power-system components
4. System trials (proof of concept experiments)
5. Testing (facilities, monitoring methods, standards)
6. Information (resource assessment, technical studies)
7. New initiatives

Funding levels during the FY 80/81 to FY 84/85 period progressed from $0.9 M (Can.) to $2.4 M (Can.), and were primarily allocated to the first four of the categories listed above.

Following termination of the NRC Solar Energy Program in 1984 the Solar Energy Development Program (SEDP) of EMR became the leading federal agency sponsoring R&D work on photovoltaics within the Renewable Energy R&D program. This program sponsors R&D in active solar energy, passive solar hybrid energy, photovoltaics, wind energy, small scale and low head hydro, and geothermal energy. The overall scope of the Renewable Energy R&D program is to develop, within Canada, technologies capable of providing a growing contribution to energy supply which is renewable, environmentally safe and cost effective, and which offers significant industrial opportunities. In FY 86/87 the SEDP awarded a total of 21 contracts for various projects on photovoltaics. EMR's contribution was $800 K (Can.), which together with contributions from the contractors and from Supply and Services Canada amounted to a total of $1.10 M(Can.).

Projects sponsored by SEDP included among others, solar cell fabrication technology development, water pumping and purification systems, batteries, controllers and inverters, and performance monitoring activities. The major portion (~ 66 %) of the EMR funds was granted to industry largely for development work, about 22% was granted to universities and R&D institutions for research, and the balance (~ 12%) to various organizations for photovoltaic related activities.

The Natural Sciences and Engineering Research Council (NSERC) has also been sponsoring photovoltaic related research (largely fundamental studies) in universities across Canada. NSERC grants most relevant to the subject for the period FY 84/85 to FY 87/88, in Canadian funds, were as follows: FY 84/85, $700 K (21 grants); FY 85/86, $800 K (25 grants); FY 86/87, $760 K (27 grants); FY 87/88, $430 K (18 grants). The reduced NSERC funding for FY 87/88 was a result of an NSERC decision not to issue new strategic energy grants, for fiscal reasons, pending a review on the subject. Most of the NSERC grants extended over a three year period and had as a common theme thin-film material research. University research funded by NSERC is reviewed in Section 8.4.

We find the overall distribution of R&D funds to be about evenly apportioned between current applications development and long-term R&D, with

SEDP funds supporting the former and NSERC funds the latter. However, we believe that the number of projects sponsored, by both SEDP and NSERC, are far too many for the limited funds available. This may be due to a perceived commitment by the sponsors to continue to support the same number of projects as earlier in the program, when more funds were available. Our view, which is based on today's costs of R&D, is that in most cases, not much can be accomplished with annual contracts less than about $100 K (Can.), particularly if they are not long-term (at least three years). Thus, for a more cost effective program, we recommend an increase in focus and, hence, a decrease in the number of contracts.

In addition, we believe that product development for most current applications is now at a stage that it can be market-driven, as opposed to R&D dollar driven. For this reason, as well as because of the need to stretch the limited R&D funds, we recommend that development funds continue to be directed to the photovoltaic industry in the form of cost-shared projects, with the government contribution increasing with the risk of the project and decreasing with the potential benefits of the project to the proponent.

8.4 CANADIAN UNIVERSITY RESEARCH

Materials research relating to photovoltaics and other thin-film applications is carried out in several universities across Canada. Such work is largely funded by NSERC and is of fundamental nature. Some of the institutions identified in this study are: McMaster University, University of British Columbia, Technical University of Nova Scotia, Universite du Moncton, Brock University, Concordia University, Universite du Quebec (Trois Riviers), University of Toronto, Carleton University, University of Guelph, Ecole Polytechnique, University of Manitoba, McGill University, University of Waterloo and University of Western Ontario. The latter six institutions were identified as being prominent in this area and some of their activities are summarized below, together with sample publications.

Groupe des Couches Minces, Ecole Polytechnique de Montreal (A. Yelon et al.)

The Ecole Polytechnique group has been active in thin film research for photovoltaic and microelectronic applications. Primarily microwave techniques have been studied for the deposition of hydrogenated a-Si. Because of the increased efficiency of microwave techniques, compared to the conventional radiofrequency plasmas, these techniques are likely to find increasing industrial applications in microelectronics. In addition, this group has been conducting fundamental studies on the structure and composition of hydrogenated a-Si films. A surface science laboratory has recently been established at Ecole Polytechnique to promote academic and industrial materials studies.

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Department of Chemistry, University of Guelph (M. Cocivera, et al.)

This group is exploring methods of electrochemical deposition of thin films of CdTe, CdSe and CdS, using organic source compounds which are more soluble in organic solvents. Such methods can lead to improved fabrication methods as well as reduced manufacturing costs. Small area cells of p-CdTe/n-CdS with efficiencies of up to 5.2% and CdTe/CdSe with efficiencies of up to 4.2%, have been reported. The group is also active in research on photocapacitance spectroscopy for measuring the bandgap density of states of thin film materials.

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Department of Electrical Engineering, University of Manitoba (H.C. Card et al.)

The group has been conducting research on polycrystalline silicon and the physics of grain boundaries. More recently the group is focusing on hydrogenated a-Si and a-SiN. The group has developed microwave plasma deposition techniques under conditions of electron cyclotron resonance. The latter method is particularly suited to microelectronics applications and is currently being applied for etching and dielectric deposition. Studies of low-

temperature deposition of microcrystalline silicon are also in progress.

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Department of Electrical Engineering, McGill University (I. Shih et al.)

Research at McGill is focusing on electrochemical deposition and characterization of $CuInSe_2$. Also, work on deposition of transparent tin- and indium-doped conducting electrodes, by radiofrequency discharges, has been reported. The group claims to have developed a low cost method for depositing $CuInSe_2$, which is in the process of being patented. Preparation of $CuInSe_2$ films by an electrophoretic deposition technique has been reported previously in the literature.

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Department of Physics, University of Waterloo (D.E. Brodie et al.)

This group has been conducting research on the preparation and characterization of thin film materials (a-Si, CdS, Zn_3P_2 and $CuInSe_2$). The main focus of the program is on the fabrication of a-Si films by vacuum deposition and simultaneous electron bombardment of the substrate. The key objective in the latter study is to increase the stability of a-Si by fabricating more ideal amorphous networks. The effect of electron bombardment on the growth and morphology of polycrystalline CdS, and "hot wall" deposition of CdS, Cu_xS-CdS, $CuInSe_2$-CdS, Zn_3P_2 and Zn_3P_2-CdS, are also being studied. A

notable spin-off from the work of this group was the development of a laser scanning microscope for thin film characterization.

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Department of Physics and Chemistry, University of Western Ontario (B.Y. Tong et al.)

Research at the University of Western Ontario is addressing fabrication and characterization of amorphous and polycrystalline silicon for semiconductor applications. Results from this laboratory indicate that post-hydrogenation of evaporated a-Si films yields good and stable semiconductor materials. A low pressure vapour deposition system, which produces materials with a low hydrogen content, was patented. The group also developed heterojunction a-Si/c-Si cells having efficiencies of about 10%.

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8.5 CANADIAN PHOTOVOLTAIC INDUSTRY

The status of the Canadian Photovoltaic industry has been revieved in previous documents [25,26,34], which together with first hand information, obtained through visits of representative sections of the industry, form the basis of our discussion below.

The Canadian photovoltaic industry is presently in the very early stages of development. There are presently five Canadian Companies involved in photovoltaics. These are listed below with the founding year, number of employees, and per cent of involvement in photovoltaics given in parenthesis following the Company's name: Bestek of Ottawa (1983, 10, 30%); Lenbrook Industries of Toronto (1977, 70, 8%); Silonex of Montreal (1958, 140, 2%); Solarpac of Toronto (1984, 12, 100%); and TPK Solar of Ottawa (1979, 22, 90%). Overall these five companies employ about forty people in photovoltaic activities. Present capabilities include photovoltaic module design and assembly, as well as design and manufacture of photovoltaic-module production-line equipment. The recent sale by TPK Solar Systems of a $3.5 M (Can.) photovoltaic plant to China is noteworthy in this respect.

According to 1984 data [34] the industry produced photovoltaic modules amounting to 27 kWp, about 0.1% of worldwide production (26 MW). By comparison, the total demand for photovoltaic modules, in Canada, for the same year was 54 kWp, of which 47 kWp was imported and 7 kWp supplied by the domestic industry. The latter indicates that for 1984 the domestic industry was more successful in the export market than the domestic one. However, data available from the same source show that the share of the domestic market has been slowly increasing (7% in 1982-83, 13% in 1984 and 15% in 1985).

The ability to compete, particularly in the domestic market, has been a major concern to the Canadian photovoltaic industry. Some of the factors cited in this respect have been the small domestic market, standards that are too restrictive, not enough financial clout, insufficient reputation, no back-up by a sizeable R&D organization, lack of government initiatives. In general, we view the majority of these concerns as those of a developing industry and we believe that most of them will become lesser-issues as the industry matures and establishes a reputation at home and abroad. Some of the factors which we believe will aid towards this goal are discussed below.

We believe that the recent establishment of a Canadian standard for photovoltaic modules (CSA-F380), following collaboration between Canadian manufacturers and users, as well as plans to upgrade the National Solar Test Facility at the Ontario Research Foundation for compatibility tests against the CSA standard, will help resolve concerns about fair competition at home.

As far as the size of the domestic market is concerned, we believe that this should be left to the market to decide, noting that significant

government intervention, like in the U.S. program, may at first generate some desirable results but there is no guarantee that these will last following withdrawal of government support. Rather than government creating fictitious markets, the industry would realize a more healthy growth if government directs funds for doing the risky R&D that industry cannot afford.

During our discussions with industry and institutional representatives, there were mixed feelings about the effect on industry of the proposed Centre for Photovoltaic R&D, as well as a broad spectrum of views as to what the Centre's mission should be. However, we believe that a Canadian Centre for Photovoltaic R&D, as described in Section 8.6, would be very valuable to the Canadian photovoltaic industry. Such a Centre would perform the risky R&D, would inform and advise industry of developments in photovoltaics, and serve as a catalyst for exploitation, in Canada, of opportunities arising from the Centre's program and from worldwide developments. It would also signal a serious commitment to photovoltaics by Canada and would provide industry the reputation of an R&D organization backing their product. We feel that this would be the most effective response to criticisms regarding government initiatives.

8.6 FUTURE STRATEGY FOR PHOTOVOLTAICS R&D IN CANADA

Our review in the preceding sections of this chapter shows that there are more than sufficient reasons for Canada to be involved in photovoltaics R&D. Certainly Canada is already benefiting from current applications of photovoltaics, even though most of the relevant technology is imported, and we should be setting ourselves in a position, through development of domestic industry, to not only supply the domestic market but also capture a fair share of the export markets.

In the long-term, we see a much wider application of photovoltaics developing in Canada, starting with photovoltaic-diesel hybrids for village power, slowly penetrating most of the oil and gas generated electricity market, entering utility grid applications for planning flexibility purposes, and eventually, depending on photovoltaic advances as well as political and economic factors that are too difficult to forecast with sufficient degree of certainty, generating a substantial (~ 5%), albeit limited, amount of electricity in Canada. This calls for advance planning to ensure that such uses of photovoltaics are developed in Canada for maximum benefit to Canadians.

We have also indicated that such applications will most certainly develop in foreign markets (third world countries) much sooner than in Canada and we should be in a position to benefit from these markets, at least to the extent that such benefits can be used to fuel R&D for subsequent applications at home. The latter calls for at least demonstration of these technologies at home even though they may not be fully economic, for it is unlikely that a foreign buyer will be willing to acquire a technology not demonstrated in the

country of origin.

Given the above, how does Canada put itself in the best possible strategic position to exploit present and forecast photovoltaic developments, given the modest R&D dollar available? To address this question we have explored three options:

1. Diversion of more of the R&D funds to strengthen the existing photovoltaic industry.

2. Diversion of more of the R&D funds for basic research in universities.

3. Centralizing some photovoltaic R&D effort in a mission-oriented national program.

We expand on these options below.

The Canadian photovoltaic industry, considering the stiff competition from the U.S.A., Japan, and Europe, has made commendable progress; however, it is still in the very early stages of development. To ensure their survival and a healthy growth, they need to focus on the secure short-term markets of existing applications, as opposed to the long-term risky R&D required to address effectively a national program on photovoltaics. Expansion of their activities to include the latter thrust will not be cost-effective and will detract from their main objectives, i.e., a good return on shareholder's equity. As indicated in the previous sections, we believe that development funds should continue to be directed to the photovoltaic industry for Canadian-specific photovoltaic applications, in the form of cost-shared projects, with the government contribution increasing with the risk of the project and decreasing with the potential benefits of the project to the proponent.

Our examination of the basic and applied component of the research performed at Canadian universities and funded by NSERC and to a lesser extent by the SEDP, shows that this is by far our strongest component in Canada at the moment. We do indeed have high quality, forefront research on the topic, which is also in the right areas, i.e., thin-film materials research. We recommend that NSERC continues to fund university research in thin-film materials research for photovoltaics as well as other spin-off applications. Nevertheless, any further expansion of photovoltaic R&D needs to be along the lines of a well defined mission oriented program, which we believe, does not fit the university culture and mandate. University research is most effective when it is curiosity driven and unencumbered by the obligations of a goal oriented mission.

Our preferred option is to centralize any additional R&D effort in photovoltaics in a well-defined, mission oriented, national program, attached to an existing R&D institution. The need of a Centre for Photovoltaic R&D has

already been recognized by the EMR Technical Advisory Committee (TAC) for Photovoltaics [136]. At its first meeting, in April 1986, the TAC recognized that Canadian photovoltaics R&D resources were too disperse for an effective R&D program and recommended consolidation into a Centre for Photovoltaic R&D which would provide a program focus, distribute R&D funds, and serve as a resource base to the photovoltaic industry. A Centre for Photovoltaic R&D, we believe, is the best option for maximizing the return on our R&D funds in this area, for the benefit of the Canadian industry and public.

A Canadian Centre for Photovoltaic R&D should have the following key objectives:

a) To conduct materials R&D aimed at the advancement of solar cell technology.

b) To maintain abreast of worldwide R&D in photovoltaics and, thereby, to inform and advise both government and industry of developments in this field.

c) To act as a resource centre and a catalyst for exploitation, in Canada, of opportunities arising from the Centre's program and from worldwide developments in photovoltaics.

The long-term scope of the Centre dictates that it be endowed with dedicated funding, for at least an initial five-year period, following which the Centre's mandate should be reviewed. The TAC recommends joint funding of the Centre by EMR and the Provincial Government and institution where the Centre will be located, at a level of about $1 M (Can.) per annum. We agree with the joint funding arrangement, because of the benefits it implies, but also because we see no other alternative in view of the funding requirements for a viable program; however, funding at about $1 M (Can.) per annum should be considered as a bare minimum and, for the reasons stated below, funding at about $1.5 M (Can.) per annum is more likely to be required.

A focussed national program should consist of a critical mass of scientists and engineers, equipped with the necessary facilities for research and development in key areas of photovoltaics. Thus, the proposed Centre would require expertise and facilities in solid state physics and chemistry, surface chemistry, electrochemistry (as it relates to batteries and film deposition methods), gas phase chemistry (as it relates to film deposition), as well as expertise in energy markets and economics. This would amount to about a dozen professional and technical positions attached to an appropriate existing institution. Total operating and capital requirements for such a group are estimated at about $1.5 M (Can.) per annum, assuming of course that the hosting institution is already well endowed in terms of the expensive facilities required for R&D on this subject and is willing to make such facilities available to the Centre.

It is important to the success of the program that the Centre's activities span the full spectrum of R&D. Too much emphasis of R would only be of academic interest and would not lead to applications and exploitation of spin-offs. On the other hand, too much emphasis on D would lack the forefront character required for innovation and for maintaining a competitive position with respect to other countries (i.e., U.S.A., Japan, Europe) that already have well established R&D programs in this area.

To maximize benefits and to bring the program "up to speed" in a short time period, considering that Canada is several years behind in this area, it is important that the hosting institution be an established R&D centre. Such an institution would not only add to the reputation of the proposed program, but it would also provide it with the necessary peripheral facilities and expertise, as well as the appropriate environment, required for a successful program.

9. CONCLUSIONS AND RECOMMENDATIONS

In this section we shall briefly summarize our major conclusions and recommendations. For the most part, these conclusions or recommendations have been directly extracted from the main text of our report and are, therefore, presented out of context. However, the appropriate section of the main text is referenced so that the full context of the recommendation or conclusion can be noted.

9.1 PHOTOVOLTAIC CELL/MODULE TECHNOLOGY

Although the cost of crystalline-silicon solar cells has decreased ten-fold within the last decade, further dramatic cost reductions will be difficult since the cost of semiconductor grade silicon is high. (Section 4.1).

Exciting advances have been made in the development of concentrator crystalline-silicon solar cells. However, this technology is not suitable for Canadian conditions. Thus, the Canadian PV research budget should not be used to support R&D in concentrator (silicon or GaAs) cell and module technologies. (Section 4.1 and 4.3).

In the long-term (after 1995 or so) the photovoltaic industry will be based on thin film technologies. The thin film materials of most promise are those based on amorphous silicon and its alloys. (Section 4.4).

An R&D program in amorphous silicon materials for photovoltaics would produce many spin-off applications. In fact, applications of amorphous-silicon materials in, for example, microelectronics and electro-optical devices, appear to be far more promising commercially than photovoltaic applications. (Section 4.4.1).

Thin-film tandem cells are necessary in order that photovoltaic utility power can become a reality. The efficiency of these cells will reach 18% by the year 2000 and the cost of the amorphous-silicon tandem cells should be less than $1/Wp by the year 2000. (Section 4.4.3).

9.2 BALANCE-OF-SYSTEM COMPONENTS

It is important, to be able to determine the annual power generated by PV stations of various designs so that relative costs can be compared. Consequently, models should be developed to simulate the power output of PV systems for different Canadian locations. These models, require reliable data on solar insolation levels and weather patterns at the proposed site of the PV station. However, historical insolation data are not always available. Thus, predictive methods are also required for estimating hourly insolation data in order to simulate the performance of PV systems. It is our recommendation that EMR continue to fund the collection of insolation data and that the funds should be made available to develop computer programs to: (1) simulate the operation of PV systems under various conditions and (2) help in the design and optimization of PV systems. (Section 5.1).

EMR should continue to provide funds to determine the performance characteristics of batteries under severe conditions in order to promote the use of PV systems in Canada's north. Furthermore, development of simulation programs that can be used to optimize PV-battery systems, including PV/diesel/battery systems, should be strongly encouraged. (Section 5.3).

Village power systems could provide an important market for PV modules until the PV utility market becomes available. PV power for remote (off-grid) villages will be the most viable application in the near-term. These stand-alone systems will not be simple PV-battery systems, especially in areas with low average insolation levels, because of the high cost of battery storage. Thus, it is expected that PV-diesel hybrid systems will be used to provide village power. To this end, we recommend that EMR should support PV-diesel hybrid demonstrations in order to accumulate design and operating experience. (Section 5.4).

9.3 GLOBAL STATUS OF PHOTOVOLTAIC R&D

Our best forecast of worldwide photovoltaic markets suggest that they will continue to grow at about the same rate as for the 1983-86 period, until further significant cost reductions and module efficiency increases are achieved. The latter are likely to be achieved by thin-film technologies within the next decade. Thus, a conservative estimate of world markets would be about 80 MWp by 1995, and about 130 MWp by 2000. These numbers were obtained by linear extrapolation of the logarithmic trend established during the 1983-86 period. Much higher forecasts were given by Frost and Sullivan

and by Maycock. We feel that both of these forecasts, which are based on significant photovoltaic penetration in utility grid applications, are too optimistic. Our examination of the technological challenges required for significant utility grid applications show that these are not likely to be met before the end of the next decade. However, we have no doubt that, once these limitations are solved, photovoltaic markets will meet and exceed even the more optimistic of the above forecasts. (Section 7.3)

9.4 CANADIAN PERSPECTIVE ON PHOTOVOLTAICS

The U.S. DOE target of generating electricity by photovoltaics at a levelized cost of 15¢ (U.S.)/kWh by the late nineties, applies to the U.S. Southwest and equivalent climates [19]. In Canada, due to the lower insolation, the same photovoltaic power plant as for the U.S. Southwest would be generating electricity at about 25¢ (U.S.)/kWh. In view of the generally lower electricity costs in Canada, due to abundant hydro and successful deployment of nuclear, the above target is uncompetitive. Thus, in order for photovoltaics to have the same impact in Canada us for the U.S. Southwest, it must be able to produce electricity at a cost of two to three times lower than that targeted by the U.S. DOE program. However, this would require technological achievements bordering presently envisaged photovoltaic limitations. Thus, significant generation of photovoltaic electricity is a much longer-term option for Canada. (Sections 6 and 8.2).

We conclude that photovoltaics are not likely to be a substantial (> 5%) component of the Canadian electricity mix early into the 21st century. However, photovoltaic substitution of oil and gas generated electricity and possibly limited deployment by utilities, for planning flexibility reasons, could generate a photovoltaic market of up to 20 GWp (~ $20 B) during the period 2000 - 2025. Even discounting possible further penetration, we believe that the above market is by itself substantial and warrants Canadian involvement in photovoltaic R&D to ensure that this market is served by Canadian industry for maximum benefit to Canada. (Section 8.2).

We find the overall distribution of Canadian R&D funds to be about evenly apportioned between current applications development and long-term R&D, with EMR funds supporting the former and NSERC funds the latter. However, we believe that the number of projects sponsored, by both EMR and NSERC, are far too many for the limited funds available. Our view, which is based on today's costs of R&D, is that in most cases, not much can be accomplished with annual contracts less than about $100 K (Can.), particularly if they are not long-term (at least three years). Thus, for a more cost effective program, we recommend an increase in focus and, hence, a decrease in the number of contracts. (Section 8.3).

We believe that development funds should continue to be directed to the photovoltaic industry for Canadian-specific photovoltaic applications, in

the form of cost-shared projects, with the government contribution increasing with the risk of the project and decreasing with the potential benefits of the project to the proponent. (Section 8.3).

Our examination of the basic and applied component of the research performed at Canadian universities and funded by NSERC and to a lesser extent by the EMR, shows that this is by far our strongest component in Canada at the moment. We do indeed have high quality, forefront research on the topic, which is also in the right areas, i.e., thin-film materials research. We recommend that NSERC continues to fund university research in thin-film materials research for photovoltaics as well as other spin-off applications. (Section 8.6).

We believe that a Centre for Photovoltaic R&D is the best option for maximizing the return on our R&D funds for the benefit of the Canadian industry and public. A Canadian Centre for Photovoltaic R&D should have the following key objectives: a) To conduct materials R&D aimed at the advancement of solar cell technology. b) To maintain abreast of worldwide R&D in photovoltaics and, thereby, to inform and advise both government and industry of developments in this field. c) To act as a resource centre and a catalyst for exploitation, in Canada, of opportunities arising from the Centre's program and from worldwide developments in photovoltaics. (Section 8.6).

ACRONYMS AND ABBREVIATIONS

AM	Air mass
ARCO	Atlantic Richfield Company
a-Si	Amorphous silicon
BOS	Balance of system
Can.	Canadian
CZ	Czochralski
DOE	U.S. Department of Energy
ECD	Energy Conversion Devices
EFG	Edge-defined film growth
EMR	Energy, Mines and Resources
EPRI	Electric Power Research Institute
eV	Electron volt
FZ	Floating-zone
J	Joule
JPL	Jet Propulsion Laboratory
LEC	Levelized electricity cost
NRC	National Research Council of Canada
NSERC	National Science and Engineering Research Council
O&M	Operating and Maintenance
PERD	Panel on Energy Research and Development
PV	Photovoltaic(s)
R&D	Research and Development
SEDP	Solar Energy Development Program
SERI	Solar Energy Research Institute
TAC	EMR Technical Advisory Committee
TRU	Techno-Economic Research Unit Limited
U.S.(A).	United States (of America)
W	Watt
Wh	Watt-hour
Wp	Peak Watt

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APPENDIX A

We have used EPRI's levelized electricity cost (LEC) equation [18,110] in order to estimate the cost of PV generated electricity. The LEC, which is calculated in \$/kWh, is the sum of the levelized capital cost for the plant (LCC) and the levelized operating and maintenance cost (LOMC), i.e.,

$$LEC = LCC + LOMC \quad .$$

For PV power plants, the LCC and LOMC can be calculated from the equations:

$$LCC = FCR \times INDC \times [\, AR(MODC + BOSA) + BOSP]/(8760 \times CF)$$

$$LOMC = PVRC \times CRF \times AR \times AOM \,/\, (8760 \times CF)$$

INDC, the indirect cost multiplier, is used to account for the indirect costs associated with installation of a PV system, e.g. engineering costs, contingency and interest during construction. We choose INDC = 1.5 for out calculations.

MODC and BOSA are the module and balance-of-system area-related costs in \$/m^2. BOSP is the balance-of-system power-related cost in \$/kW. MODC and BOSA are varied in our calculations whereas BOSP is set equal to \$250/kW. AOM is the annual operating and maintenance cost in \$/m^2. In our calculations AOM = \$2.28/m^2.

AR is the plant aperture area required to generate 1 kW AC of power under peak operating conditions:

$$AR = 1 \,/\, (\text{Average Peak Insolation})(\text{System Efficiency})$$

where, the System Efficiency is the product of the balance-of-system (BOS) efficiency (0.81) and the efficiency of the module under nominal operating conditions. CF is the annual system capacity factor, i.e. the ratio of energy produced divided by the product of peak capacity times the number of hours in the year. The Average Peak Insolation, the nominal module efficiency and the capacity factor are all site specific [18]. The nominal module efficiency is site specific because it depends on the average ambient temperature at the site of the PV station.

FCR, the fixed charge factor (also known as the levelized carrying charge) is given by the formula [137]:

$$FCR = k \,/\, [1 - (1 + k)^{-N}]$$

where, k is the discount rate and N is the "write-off" period in years. In our

calculations we use EPRI's value for N, i.e. N = 10. CRF, the capital recovery factor, is given by the formula for FCR except that N, in this case, is equal to the lifetime of the plant, i.e. 30 years. Finally, PVCR, the present value of recurring costs, can be calculated [137] using the equation:

$$PVCR = (1 + i)/(k - i) \times [\ 1 - (1 + i)^N/(1 + k)^N\ ]$$

where, i is the inflation rate and N is the lifetime of the plant. In most of our calculations we have chosen: k = 12.5% and i = 8.5%. However, we vary k and i in order to determine the effect of these parameters on the LEC.

A sensitivity analysis on the LEC equation is easily carried out. Essentially, this involves the calculation of the derivative of LEC with respect to the various parameters. The sensitivity analysis shows that the LEC is not very sensitive to changes in the value of AOM, i.e. for most cases LOMC is small compared to LCC, or the value of BOSP, i.e. the area related costs are more important in determining the value of LCC. In the light of these results, it is not surprising that LEC has approximately the same (absolute) sensitivity to changes in the capacity factor, the insolation level, the module efficiency, the fixed charge rate (FCR), or the sum of the module plus BOS-area costs. This is illustrated in Table A.1.

We also apply EPRI's equations to estimate the cost of electricity produced from hydro, coal or nuclear stations. For these cases, we replace: (1) the term AR(MODC + BOSA) in the equation for LCC by the capital cost of the power plant, in $/kW, and assume that the BOSP costs are included in the capital costs of the plant and (2) the factor [AR x AOM / (8760 x CF)] in the equation for LOMC by the O&M costs of the power plant in $/kWh.

TABLE A.1
SENSITIVITY ANALYSIS FOR LEC

Parameter x	Value of x	Derivative of LEC With Respect to x	Estimated Change in the LEC ($/kWh) Caused by a 50% Increase in x
CF	0.28	-0.57	-0.080
FCR	0.19	0.78	0.071
INDC	1.50	9.4×10^{-2}	0.071
Insolation	1.0 kW/m^2	-0.13	-0.066
Module Effi iency	0.15	-0.88	-0.066
MODC + BOSA	\$125/m^2	9.1×10^{-4}	0.057
BOSP	\$250/kW	1.1×10^{-4}	0.014
AOM	\$2.28/m^2	7.7×10^{-3}	0.009